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Corresponding Author: Dr. Jie Zhu, PhD

Corresponding Author's Institution: University of Nottingham

First Author: Yuanlong Cui

Order of Authors: Yuanlong Cui; Jie Zhu, PhD; Stamatis Zoras; Yaning Qiao; Xin Zhang

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Highlights:

- 25 years' PV/T-HP system performance and life cycle cost are investigated.
- Cumulative system energy cost surpasses initial cost at the end of the 4^{th} year.
- Cumulative PV/T-HP savings exceed principal balance by the end of the 5^{th} year.
- PV/T-HP with high net present value and short payback period has low initial cost.
- The system payback period is 4.15 years.

Energy performance and life cycle cost assessments of a photovoltaic/thermal assisted heat pump system

Yuanlong Cui [a], Jie Zhu [b,*], Stamatis Zoras [a], Yaning Qiao [c], Xin Zhang [d]

[a] Department of Built Environment, College of Engineering and Technology, University of Derby, Derby, DE22 3AW, UK

[b] Department of Architecture and Built Environment, University of Nottingham, Nottingham, NG7 2RD, UK

[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, 221116, China

[d] School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK

Abstract

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* Corresponding author. Tel: +44-115-8466141 Fax: +44-115-951315
E-mail address: jie.zhu@nottingham.ac.uk

1. Introduction

Climate change has an increasing negative impact on our planet [1] and leads to global warming and ozone layer depletion. The greenhouse gas from fossil fuel is widely recognised as the key contributor towards the climate change. Currently, the energy consumption in building sector makes up around 40% of the total energy usage in European, therefore enhancing energy efficiency and adopting renewable energy are becoming more significant in this sector [2, 3]. This paper presents an alternative measure to provide electrical and thermal energy for a domestic building by using a hybrid renewable energy system.

In the past several years, the solar electricity applications have been increased hugely based on photovoltaic (PV) technology [4, 5]. The mean efficiencies of mono-crystalline and poly-crystalline modules have been improved from 12% to 17% and from 10% to 16%, respectively. This denotes that merely less than 20% of received solar radiation could be transformed into electricity, whereas more than 80% of the received solar energy is dissipated [6, 7]. The PV panel efficiency could be increased by using active or passive cooling method [8, 9], many researchers employed air and water to cool the PV panel with the extracted heat for various purposes, and found that water is superior to air in terms of cooling effect [10,11].

In order to enhance PV panel efficiency and take full advantage of the residual heat, the PV and thermal technologies are combined to form a single knowledge called Photovoltaic/Thermal (PV/T) technology. This technology can simultaneously generate heat and electricity with high energy efficiency compared with the separated units. Many researches on the PV/T module have been reported. Bigorajski and Chwieduk [12] investigated the performance of a PV/T module for single family house in Poland, and found that during winter months electrical and thermal efficiencies of the PV/T module reach approximately 11-12% and 18-19%, respectively. Huang et al. [13] tested a PV/T module consisting of a pump, a 120-L storage tank and a 240-W poly-crystalline silicon collector, and discovered that the module electrical and thermal efficiencies could achieve 12.77% and 35.33%, respectively. Herrando et al. [14] established a mathematical model for the PV/T module to evaluate electricity and heat outputs for a three-bedroom terraced house in the UK, and concluded that 51% of electricity and 36% of space heating demands could be met by the PV/T module, resulting in an annual saving of 0.8 tons of carbon dioxide. Aste et al. [15] setup a numerical model of the PV/T module and assessed its precision via using experimental data in Italy, and obtained that the module mean daily electrical and thermal energy efficiencies could reach 6% and 25%, respectively. Bianchini et al. [16] investigated a commercial PV/T system to supply electrical and thermal energy for a residential building in the central area of Italy, and concluded that the system could produce approximately 1362 kWh electricity and up to 443 kWh heat annually. Ramos et al. [17] carried out an energy assessment of the PV/T modules for the domestic buildings in different European locations, and confirmed that the presented modules are able to cover 60% of heating need and almost 100% of electricity requirement of the households.

Currently, several researches on the PV/T hybrid system have also been implemented to enhance the system electrical and thermal energy production. Bellos and Tzivanidis [18] utilized PV/T panels to drive a heat pump system to investigate the system performance, and found that the daily power and heating generation are 5.13 kWh and 34.9 kWh, respectively. In the meantime, the average energy and exergy efficiencies achieve 8.80 % and 65.9%, respectively. Zhou et al. [19] developed a novel heat pump system by integrating photovoltaic and thermal panels for space heating under low solar radiation condition, and obtained that the average thermal and electrical efficiencies are 33.4% and 15.9%, respectively. The mean thermal efficiency of the thermal panels could reach 60.4%, the COP of the heat pump is 4.7. Cai et al [20] developed a dual source heat pump water heater where a direct expansion PV/T evaporator and an air source evaporator operate parallel to absorb heat from the solar radiation and ambient, respectively. It is found that when the solar irradiation increases from 100 W/m^2 to 300 W/m^2, the Coefficient of Performance (COP) of the hybrid system increases from 2.25 to 2.66. In addition, when the ambient temperature varies from 10 °C to 30 °C, the COP of the hybrid system rises by 18.22%. Vallati et al. [21] investigated a PV/T assisted heat pump to provide electricity for the water source heat pump and thermal energy for building space heating in Craow, Milan and Roma based on different climate conditions. Their results demonstrate that when thermal and electrical efficiencies of the PVT are set respectively to 0.6 and 0.15, the heating requirement can be covered by 47% for Cracow, 62% for Milan and 70% for Rome. Lu et al. [22] proposed a PV/T with heat pump system using vapour injection cycle to harvest thermal energy and electric power in cold winter. Their results reflect that the total generated heat and electricity of the system reach 23.68 kWh and 0.51 kWh, respectively. Moreover, the average thermal COP_{th} and PV/T COP_{PVT} values are 3.27 and 3.45, respectively. Xu et al. [23] developed a PV/T with heat pump (PV/T-HP) system in Nanjing, China, which could achieve a mean COP of 4.8 and an electrical efficiency of 17.5% on a sunny day. Wang et al. [24] designed a multi-function PV/T-HP system for domestic building application, and denoted that the system mean thermal efficiency is approximately 37% and the heat pump COP ranges from 2.5 to 3.2. Zhou et al. [25] investigated an innovative hybrid PV/T system with novel mini channel and a heat pump for space heating, and concluded that the hybrid system reaches the mean solar efficiency of 45.0% and average COP of 4.9. Chen et al. [26] performed a study numerically and experimentally on an innovative heat-pipe solar PV/T-HP system, and discovered that high ambient temperature, solar radiation and PV backboard absorptivity contribute to the heat pump COP improvement.

Most economic evaluations regarding the hybrid PV/T system concentrate on the fundamental indicators and are performed by the life cycle cost (LCC) assessment method, such as levelized cost of heat (LCOH), levelized cost of energy (LCOE), net present value (NPV) as well as simple/discounted payback period (PBP). Riggs et al. [27] conducted an economic analysis for an innovative hybrid PV/T module based on the LCOH approach in the United States, and concluded that the PV/T with waste heat recovery could increase the lowest LCOH. Bianchini et al. [16] compared a PV/T system with the separated flat plate solar collector and PV module by the LCOE approach, and confirmed that the PV/T system is more economical in comparison to the separated systems. Gu et al. [30] performed an economic study for the PV/T technology based on Monte Carlo method in Sweden, and found that the capital investment on the PV/T module could be profitable since the planned earnings exceed the expected expenses over the whole lifetime period. Meanwhile, according to their sensitivity analysis, the solar irradiance, heating price and debt to equity ratio have high impact on the module PBP which ranges from 6 to 10 years. Thygesen and Karlsson [31] investigated the economic benefits of a PV heat pump (PV-HP), a solar thermal heat pump (SHP) and a PV/T-HP system by using the NPV approach, and demonstrated that the PV-HP system is the most cost-effective and has the highest solar energy fraction in comparison to the SHP and PV/T-HP systems. Buker et al. [32] performed the LCC assessment for a PV/T module in the UK, and obtained that the NPV reaches €19456.14 with an 11-year PBP. Zhang et al. [33] carried out the PV/T-HP economic analyses in Stockholm, London and Madrid by means of the NPV and PBP methods, and found that the yearly running expenses could be saved €2051.4, €1667.0 and €2768.7 respectively in above three locations. Moreover, the PBPs of all three locations are less than 5 years. Herrando and Markides [34] undertook an economic investigation of a hybrid PV/T system for distributed power and hot water supplies in London, UK, and discovered that the PBP is in the range of 10 to 13 years, which depends on the variations of inflation and discounted rates.

For these studies, only a few researchers deliberated the present values of both costs and savings whereas the remaining only took into account the present value of cost. Also in most cases, LCOE, LCOH, NPV are only determined by point values for all inputs parameters, disregarding the integrated uncertainty for investment decision. These methods are restricted because they could not provide a sense of the likelihood of different outcomes, resulting in a certain disagreement in real case. By comparison, the Monte Carlo simulation is an effective approach to solve complex economic assessment, which is a comparatively simple and established technique for including uncertainty and risk in quantitative model. In the Monte Carlo model, a calculation is carried out many times (usually hundred to millions), and each time with a set of input parameters is selected randomly based on the pre-defined distributions for each estimation. For example, Meschede et al. [35] analysed the effects of probabilistic distributed factors on PV system performance for hotels by means of Monte Carlo simulation, and concluded that occupancy fluctuation and weather condition are sensitive to investment decision. Meanwhile, Monte Carlo simulation contributes to defining the average of the annuity more precisely and to rate the risk of fluctuating weather and occupancy better. Rezvani et al. [36] performed a techno-economic evaluation of solar water heaters in Australia based on Monte Carlo simulation, and revealed that the solar water heaters could provide better long-term economic viability significantly in comparison with traditional systems at moderate auxiliary energy consumptions. Gu et al. [37] implemented a techno-economic analysis of a solar PV/T concentrator in Sweden through Monte Carlo simulation, and found that the solar irradiance, local heating price, product capital price, discount rate and debt to equity ratio have significant effects on the decision-makings of long-term investment in building sector.

Even though this approach has been utilized in standalone PV, solar thermal and PV/T domains for several years, currently there are rarely economic assessments of hybrid PV/T-HP by using the Monte Carlo simulation. This paper therefore fills the research gap by providing in-depth techno-economic analysis of the hybrid PV/T-HP system for a long-term operation period. To be more specific, the 25 years' cumulative NPV of a hybrid PV/T-HP system for the domestic building application in the UK is studied by considering several vital parameters including the initial cost (IC), system energy cost (SEC), mortgage payment (MP), maintenance expense (ME), periodic cost (PC), system income tax savings (ITS) and present worth of money under the FiT and RHI schemes. The PBP is attained by the SEC and cumulative cash flows, the sensitivity analyses of economic model are achieved as well. Furthermore, the annual electrical energy savings, total energy savings and PBP are compared for the FiT and new Smart Export Guarantee (SEG) schemes.

2. Hybrid system energy and economic models

A hybrid PV/T-HP system is used to meet heat and electricity demands of a domestic building in this study. A basic design schematic of the system is illustrated in Fig. 1, it mainly comprises of a water-based glazed PV/T module employing a polyethylene heat exchanger (PHE), a water-to-water heat pump unit, an inverter, a hot water tank and a circulation pump. The PV/T module provides electricity for the heat pump and water pump and heat for the heat pump evaporator.

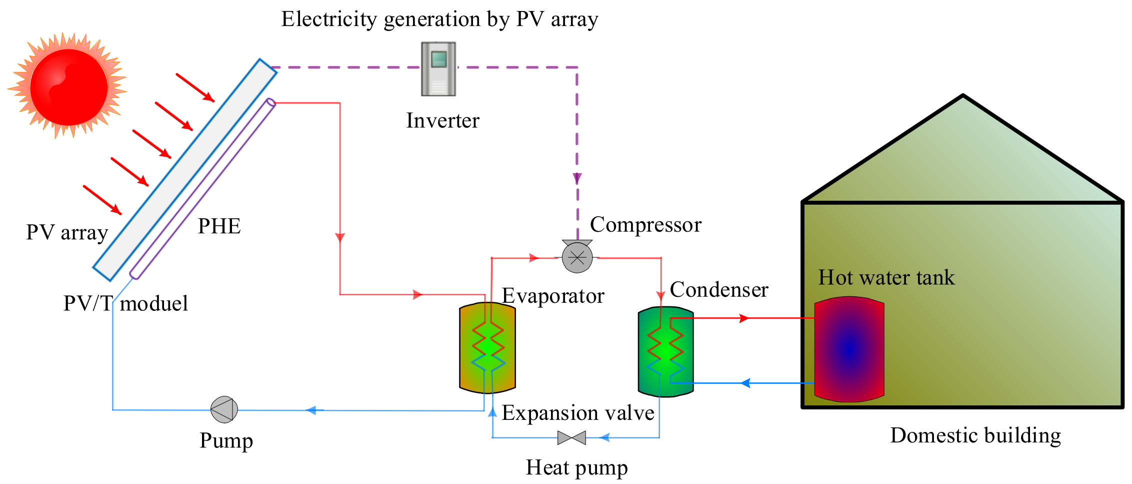


Fig. 1. The diagram of the PV/T-HP system applied in domestic building

2.1 Energy models

2.1.1 Photovoltaic/Thermal model

The PV/T module comprises of glass cover, PV array, ethylene-vinyl acetate (EVA) layer, PHE tube and adiabatic material layer. The solar cells are located in between two transparent tedlar-polyester-tedlar layers, and the EVA is placed behind the PV array. This forms a thermal conduction and electrical insulation structure, and the adiabatic material layer is set at the back of the PHE to minimize heat loss. A cross-sectional view of the PV/T module is given in Fig. 2. To be more specific, the solar radiation is transformed into electricity by PV array, meanwhile, thermal energy is absorbed by the working fluid within the PHE, and then passed to the heat pump evaporator.

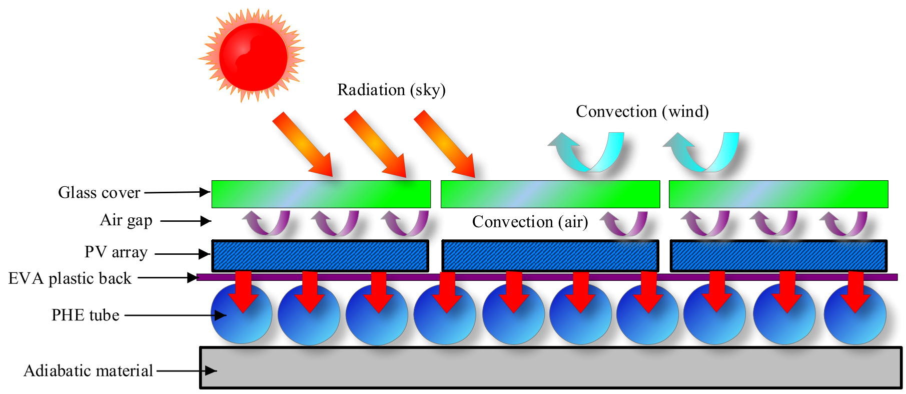


Fig. 2. A cross-sectional view of the PV/T module

In order to reduce the computing time and simplify the determination process, some assumptions are established as follows:

1) The module is at a quasi-steady state.

2) All material layers have homogeneous surface temperatures.

3) Heat loss across the piping system is ignored.

4) The air between the PHE tube and PV array is at the stagnant state.

5) Heat loss across the adiabatic material is negligible.

Therefore, the system energy conservation equation is given as:

$$\frac{\partial Q_{PV/T-thermal}}{\partial t} = Q_{absorber} - Q_{PV/T-loss} - Q_{electricity} \quad (1)$$

where $Q_{PV/T\text{-}thermal}$ is the useful thermal energy (kW); t is the time (s); $Q_{absorber}$ is the solar energy absorbed at the front of the PV/T surface (kW); $Q_{PV/T\text{-}loss}$ is the total heat loss (kW); $Q_{electricity}$ is the overall electricity output (kW).

$Q_{absorber}$ is calculated as follows:

$$Q_{absorber} = \tau_c \alpha_{absorber} A_{actual} I \quad (2)$$

where τ_c is the PV/T transmittance; $\alpha_{absorber}$ is the PV/T absorptivity ($\alpha_{absorber}$=0.9); A_{actual} is the PV/T actual area (m^2); I is the incident solar radiation (W/m^2).

The heat losses include the convection heat exchanges between the cover layer and ambient air ($Q_{conv,c,a}$), and between the EVA and PHE ($Q_{conv,\ EVA,\ PHE}$); the emissive powers (EP) between the cover layer and sky ($Q_{EP,c,\ sky}$), and between the EVA and PHE ($Q_{EP,EVA,PHE}$).

$$Q_{PV/T-loss} = Q_{conv,c,a} + Q_{EP,c,sky} + Q_{conv,EVA,PHE} + Q_{EP,EVA,PHE} \quad (3)$$

$$Q_{conv,c,a} = h_{conv}(T_c - T_a) \quad (4)$$

where h_{conv} is the forced convection coefficient of the ambient air, that can be approximated as a function of wind speed and given as [32, 38-40]:

$$h_{conv} = 5.7 + 3.8 \cdot V_{wind} \tag{5}$$

In order to get the glass cover temperature, the following empirical equation is adopted [38, 39]:

$$T_c = 30 + 0.0175 \times (I - 300) + 1.14 \times (T_a - 25) \tag{6}$$

where V_{wind} is the wind velocity (m/s); T_c is the PV cover temperature (°C); T_a is the ambient air temperature (°C).

The EP between the cover layer and sky is given as:

$$Q_{EP,c,sky} = \varepsilon_c \cdot \sigma \cdot (T_c^4 - T_s^4) \tag{7}$$

where ε_c is the PV/T cover layer emissivity (ε_c =0.96); σ is the Stefan-Boltzmann's constant, $5.67\text{x}10^{-8}$ $W/m^2 \cdot K^4$; T_s is the sky temperature (°C).

The sky temperature is calculated via Swinbank's equation [38, 39]

$$T_s = 0.037536 \cdot T_a^{1.5} + 0.32 T_a \tag{8}$$

The convection heat exchange between the EVA and PHE is given as:

$$Q_{conv,EVA,PHE} = h_{air} \cdot (T_{EVA} - T_{PHE}) \tag{9}$$

where h_{air} is the natural convective heat transfer coefficient between the PV array and PHE ($W/m^2 \cdot K$); T_{EVA} is the EVA plastic layer temperature (°C); T_{PHE} is the PHE outer wall temperature (°C).

h_{air} is written as:

$$h_{air} = \frac{N_u \cdot \lambda_{air}}{\delta_{air}} \tag{10}$$

where λ_{air} is the air thermal conductivity (W/m·K); δ_{air} is the air gap between the PV layer and glass cover (m).

Nu is the Nusselt number as follows:

$$Nu = [0.06 - 0.017(\frac{\beta_s}{90})]Gr^{1/3} \tag{11}$$

where β_s is the title–angle of PV array; Gr is the Grashoff number as given [38, 39]:

$$Gr = \frac{g \cdot (T_{pl} - T_{heo}) \cdot \delta_{air}^3}{\nu_{air}^2 \cdot T_{air}} \tag{12}$$

Hence, the EP between the EVA and PHE is given as:

$$Q_{EP,EVA,PHE} = \varepsilon_{EVA} \cdot \sigma \cdot (T_{EVA}^4 - T_{PHE}^4) \tag{13}$$

where ε_{EVA} is the EVA plastic layer emissivity.

The PV electrical efficiency can be obtained based on the temperature function [38, 39]:

$$\eta_{electricity} = \eta_{ref} [1 - \gamma_p (T_{absorber} - T_{ref})] \tag{14}$$

where $\eta_{electricity}$ is the PV array electrical efficiency (%); η_{ref} is the PV array efficiency at reference temperature (%); γ_p is the PV cell temperature coefficient (γ_p= 0.035 °C^{-1}); $T_{absorber}$ is the absorber surface temperature (°C); T_{ref} is the reference temperature (°C).

The total electrical energy is written as:

$$Q_{electricity} = \eta_e A_{actual} I \tag{15}$$

The thermal efficiency of the PV/T module is expressed as:

$$\eta_{thermal} = \frac{Q_{PV/T-thermal}}{A_{actual} \cdot I} \tag{16}$$

where $\eta_{thermal}$ is the thermal efficiency (%).

2.1.2 Heat pump model

A mechanical heat pump is coupled with the PV/T module in this case. Based on the local weather condition, the heat pump is assumed to run for heating purpose. Considering the influence of the compressor rotational speed, its electricity consumption is illustrated [41]:

$$m_r = V_c \omega \rho_{r,suc} \cdot [1 + C_v (1 - \frac{P_{r,cond}}{P_{r,evap}})^{\frac{1}{n}}] \tag{17}$$

$$\Delta\xi_{comp} = \xi_{r,dis} - \xi_{r,suc} = \frac{n}{n-1} \cdot \frac{P_{r,evap}}{\rho_{r,suc}} \cdot [(\frac{P_{r,cond}}{P_{r,evap}})^{\frac{n-1}{n}} - 1] \tag{18}$$

$$W_{comp} = \frac{m_r \Delta\xi_{comp}}{\eta_{comp}} \tag{19}$$

where m_r is the refrigerant mass flow rate (kg/s); ω is the compressor rotating speed (rev/s); V_c is the compressor suction volume (m^3); $\rho_{r,suc}$ is the compressor inlet working fluid density (kg/m^3); C_v is the clearance factor; P is the pressure (kPa); n is the refrigerant polytropic compression coefficient; ξ is the specific enthalpy (kJ/kg); $\Delta\xi$ is the specific enthalpy change (kJ/kg); η_{comp} is the compressor overall efficiency (%); W_{comp} is the compressor electricity consumption (kW).

The pressure drop of the working fluid within the PV/T module is determined through the friction factor (f) in the Darcy Weisbach equation [39], and expressed as:

$$\Delta p = f \frac{L}{D_H} \frac{\rho_{fluid} V_{fluid}^2}{2} \tag{20}$$

where L is the length of the PV array (m); D_H is the PHE tube hydraulic dimeter (m); ρ_{fluid} is the working fluid density (kg/m^3); V_{fluid} is the working fluid velocity in PV/T module (m/s).

The circulation pump electricity consumption is obtained by:

$$W_{pump} = \frac{\Delta p \times m_{pump}}{\rho_{fluid} \eta_{pump} / 100} \tag{21}$$

where η_{pump} is the pump efficiency (%); m_{pump} is the mass flow rate (kg/s).

2.1.3 Heat pump performance

The system useful heat (Q_{useful}) is equal to ($Q_{PV/T\text{-}thermal} + W_{comp} + W_{pump}$). Furthermore, the COP in heating mode is given as:

$$COP = \frac{Q_{useful}}{W} = \frac{Q_{PV/T-thermal} + W_{comp} + W_{pump}}{W_{comp} + W_{pump}} \tag{22}$$

2.2 Economic model

Economic policies have significant influence on the LCC assessment for the hybrid PV/T-HP system, such as tariff structure, fossil fuel penalty and renewable subsidy. The subsidy comes in different forms including investment rebate, Feed-in Tariff (FiT) and Export Tariff (ET) for renewable electricity and Renewable Heat Incentive (RHI) for renewable heat production. To obtain the accurate LCC evaluation results, the system boundary should be identified at first, which includes its scope and lifetime. The scope of the PV/T-HP system comprises of the PHE, PV array, inverter, heat pump and piping system. The lifetime of the PV/T-HP system is about 25 years [27, 32, 33, 37], which is adopted in this case as well. The inverter has a 5-year manufacturer warranty and is anticipated to be replaced at the end of each 5-year period. Based on the international standard of environmental management BS ISO 15686 [42], the LCC is the total expense of the PV/T-HP system in all stages from manufacture to disposal, and involves initial cost (IC), maintenance expense (ME), mortgage payment (MP), periodic costs (PC), system energy cost (SEC) and income tax savings (ITS) [37, 39].

To be more specific, the MP is a monthly payment made to pay back a mortgage, which consists of principal payment and interest of money on the loan borrowed for system installation [43, 44]. The principal portion is used to pay off the original loan whereas the interest is paid to the lender. For the property in this paper, it means that the system costs for the PV/T modules, inverter, PHE, ground pipes, water pump, heat pump, refrigerant and labour, are borrowed from a bank. Moreover, the PC are also known as periodic fixed costs. To keep the system in operating condition, some periodic costs, such as operation and maintenance costs, need to be paid. The PC denote the replacement costs of main system parts. For the hybrid PV/T-HP system, the inverter used in the system needs to be replaced after certain period of time, this cost is much more expensive compared with the annual maintenance fee. Basically, it is expected to be replaced at the end of each 5-year period [32, 40]. The heat pump is required to be replaced every 20 years [45]. Furthermore, the SEC is also known as the fuel cost saving, which is the total cost of household electricity and heat demands. The LCC of the PV/T-HP system is expressed as follows:

$$LCC = E_{IC} + \sum_{i=1}^{n}(E_{SEC} + E_{MP} + E_{ME} + E_{PC} + E_{ITS}) \tag{23}$$

where LCC is the system lifespan expense (£); E_{IC} is the initial cost including construction and engineering design expenses (£); E_{SEC} is the system energy cost in present worth (£); E_{MP} is the yearly mortgage payment in present worth (£); E_{ME} is the system maintenance expense in present worth (£); E_{PC} is the system periodic cost in present worth (£); E_{ITS} is the system income tax savings in present worth (£).

The MP composes of the principal payment (PP) and interest payment (IP), which can be given as:

$$E_{MP} = Z \times \frac{d_{MP} \cdot (1+d_{MP})^{Y}}{(1+d_{MP})^{Y}-1} \tag{24}$$

where Z is the PP (£); d_{MP} is the yearly interest rate (%); Y is the number of MP years.

To maintain the PV/T-HP system in good operating condition, some expenses for operation and maintenance are required. The $E_{PVT\text{-}HP\ savings}$ is defined as the annual net cash flow [38, 40]:

$$E_{PVT-HP\ savings} = E_{SEC} - E_{MP} - E_{ME} - E_{PC} - E_{EPT} + E_{ITS} + E_{RHI} + E_{FIT} + E_{ET} \tag{25}$$

where E_{ET} is the Export Tariff that is paid for any surplus electricity sold to the grid.

The ITS of the PV/T-HP system can be expressed as [38, 40]:

$$E_{ITS} = E_{ETR} \times (E_{MP} + E_{EPT}) \tag{26}$$

where E_{ETR} is the effective tax rate (%); E_{EPT} is the extra property tax (£).

In this study, the NPV is adopted to assess a single investment whether is acceptable or not. The NPV is obtained by subtracting the present values of cash outflows (including initial investment) from the present values of cash inflows over the PV/T-HP life time. The higher the NPV, the higher the benefit. Thereby, the NPV is expressed as:

$$NPV = -E_{IC} + \sum_{N=1}^{N'} \frac{E_{N}}{(1+k)^{N}} \tag{27}$$

where E_N is the net cash inflow during the N period year (£); N is the number of time periods; k is the discount rate (%).

The PBP is given as:

$$PBP = x + \frac{y}{z} \tag{28}$$

where x is the number of years before full recovery; y is the unrecovered cost at the start of the year (£); z is the cash flow during the year (£). The PBP is utilized to calculate the period to recoup an investment, and it provides a more accurate indication by discounting each cash flow and considering the time value of money. What is more, the investment is considered financially viable if the payback time is lower than the expected lifetime of the investment.

3. Methodology

3.1 Domestic building

The selected domestic building, as shown in Fig. 3, is a detached house in Nottingham, UK, which is situated at 52.97° N and 1.10° W. It has four bedrooms with a total floor area of 134.64 m^2 and its roof area on the south side is 38.86 m^2. The building is designated for a family with 4 persons. Its main thermal energy is used for space heating and hot water whereas the electrical energy is used for fridge, washing machine, TV, computer, boiler, shower, lighting, cooker, microwave, dishwasher, etc.

Fig. 3. Location and photo of the detached house in Nottingham

3.2 Weather condition and energy demands

Meteorological data are essential for the accurate energy output of the hybrid PV/T-HP system and building energy load. The local mean ambient air temperature and solar radiation are presented in Fig. 4 [46]. The local highest mean temperature reaches 18.41 °C in August, while the lowest is 5.28 °C in January. Meanwhile, the monthly average solar radiation of Nottingham ranges from 14.79 kWh/m^2/month in December to 144.62 kWh/m^2/month in June [46]. The monthly average wind speed is in the range of 3.07 m/s to 4.49 m/s. The monthly building energy demands (thermal and electrical) are displayed in Fig. 5, which are obtained from the British Gas supplier. Specifically, the maximum and minimum thermal energy demands are 2673 kWh in January and 910 kWh in August, respectively. The largest electricity demand is 540.36 kWh in December whereas the smallest is 92.11 kWh in June. Furthermore, the building annual thermal and electrical energy demands reach 22087 kWh and 3874.71 kWh, respectively.

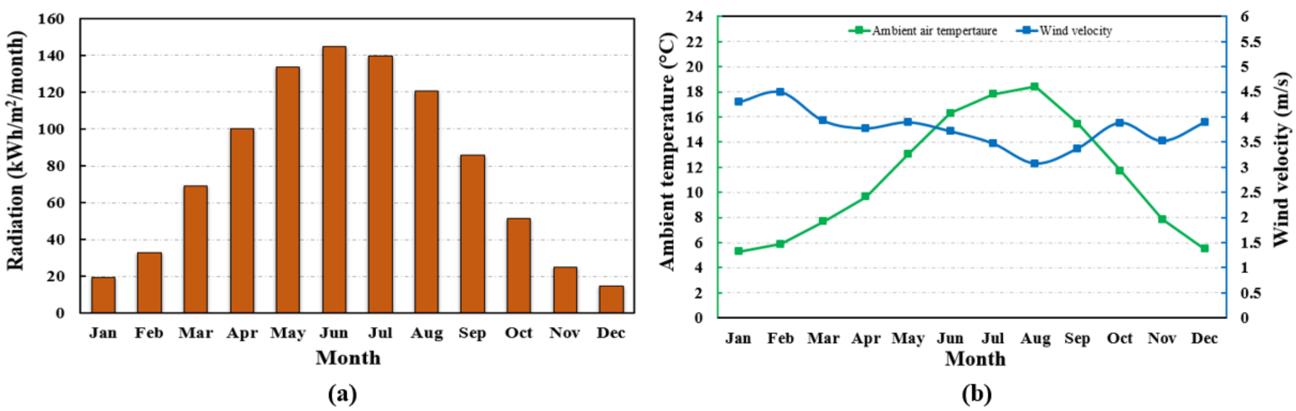


Fig. 4. Weather condition: (a) global irradiation; (b) wind velocity and ambient air temperature in Nottingham

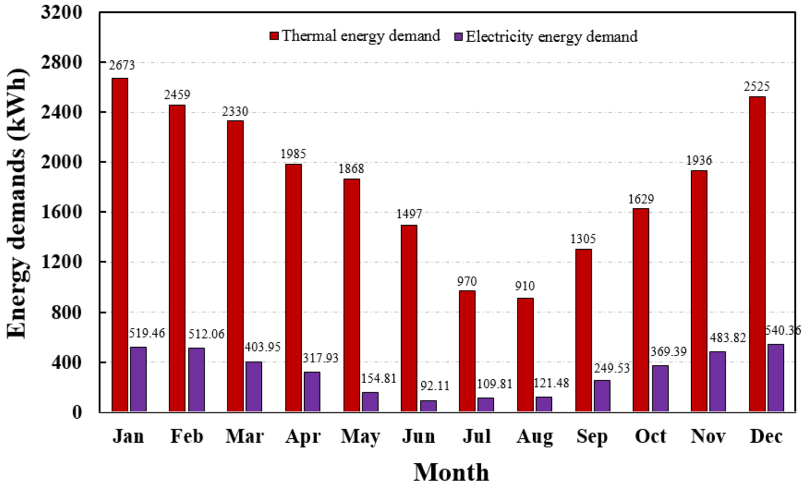


Fig. 5. Monthly building heat and electricity demands

3.3 System parameters

The design of the hybrid PV/T-HP system, specifically the determination of the component size in each application, is challenging because of a large number of factors involved, such as fluctuations in energy demand, uncertainties existing in renewable resources, precarious energy prices and complex interaction among components. Moreover, the PV/T performance depends on the location weather condition, and this must be accurately modelled for the optimal configuration to be achieved. Furthermore, the initial investment from the homeowner is a significant factor that requires to be considered during the whole design process. Therefore, 18 (250Wp) CS6P-250P photovoltaic solar arrays from Canadian solar company are utilized in the PV/T module based on the building electricity consumption, and installed at a 30° tilt angle oriented to the south. The arrays have anti-reflex coatings to increase the light absorption. The solar cell is polycrystalline silicon with the efficiency of 15.54% [47], and its operational temperature ranges from -40 °C to 85 °C. A 4.5 kW Afore HNS4500TL inverter is adopted to transform direct current (DC) into alternating current (AC). The PHE tube has the interior and exterior diameters of 0.0029 m and 0.0045 m, respectively. The water flow rate within the PHE is in the range of 2 L/min (0.12 m^3/hour) to 6 L/min (0.36 m^3/hour). Furthermore, the PHE is linked to a 5.5 kW IVT Greenline heat pump [45] that provides hot water at a temperature range from 35 °C to 65 °C. The technical details of the PV/T-HP system are shown in Table 1.

Table 1 Technical parameters of the PV/T-HP system [45, 47]

Component	Description	Value
CS6P-250P PV module	Module dimensions	1638 × 982 × 40 mm
	NO. of PV panels	18
	Cell type	Polycrystalline
	Packing factor	0.92
	Conversion efficiency	15.54%
	Nominal max. power	250 W
	Maximum current	8.30 A
	Maximum voltage	30.10 V
	Short circuit current	8.87 A

	Open circuit voltage	37.20 V
	Active total area	26.6 m^2
	Title angle	30°
	Manufacturer warranty	25 years
PHE module	The internal diameter of pipe	0.0029 m
	The external diameter of pipe	0.0045 m
	Spacing between PHE tubes	0.1 m
	Max temperature allowed in PHE	60 °C
	Max pressure allowed in PHE	1 MPa
	Mean mass flow rate	4.8 L/min
	Length	8 m
	Width	1 m
Heat pump	Emitted /Supplied output at 0/35°C	5.5/1.3 kW
	Refrigerant R407C mass flow rate	0.02 kg/s
	Operation temperature heat transfer system	-5 to 20 °C
	Nominal flow heating medium	0.30 l/s
	Minimum flow heating medium	0.20 l/s

3.4 Cost breakdown

The IC of the entire system is £12015 with 10% deposit, the rest of the IC is paid in a period of 25 years at an interest rate of 7%. The ME is assumed to be paid annually with an inflation rate of 4.5% [32]. The property tax is 2% of the initial investment whereas the ME for the PV/T-HP system is £120/year. The mean effective income tax rate (ITR) is estimated to be 20% during the LCC period. The ME and main installation expenses for the PV array, inverter, PHE, piping line and heat pump, are presented in Table 2, and the FIT, ET and RHI are considered as well in this study. According to the energy prices regulated by Office of gas and electricity markets [48] in the UK, the electricity price at FIT for homes is £0.1097/kWh whereas the electricity price at ET for supplying electricity into the grid is £0.052/kWh [48], the RHI for domestic building is £0.0895/kWh [49]. The detail component prices and economic parameters are displayed in Table 3.

Table 2 PV/T-HP system cost breakdown

Item	Value
PV/T	
PV arrays	£2273
Inverter	£670
PHE (×2)	£500
Pipe	£300
Pump (×1)	£45
Estimated PV/T unit cost	£3488
Heat pump	
Heat pump & commissioning	£5600
Refrigerant expense	£174
Estimated heat pump system expense	£5744
Other costs	
Header circuit insulation	£186
Brass fittings	£747
Estimated other equipment expense	£933
Labour costs	£1550
Total initial expense	£12015
Estimated maintenance expense	£120

Table 3 Parameters utilized for financial assessment

Item	Value
Electrical price	Feed-in tariff (building usage): £0.1097/kWh Export tariff (to the grid): £0.052/kWh
RHI for heat pump	£0.0895/kWh
Deposit payment	10%
Inflation rate of electricity price	6%
Interest rate of principal	7%
Inflation rate of maintenance	4.5%
Inflation rate of inverter price	3%
Council tax for property tax	2%
Inflation rate of extra property tax	4%
Income tax rate	20%
UK discount rate	8.75%

3.5 Program algorithm

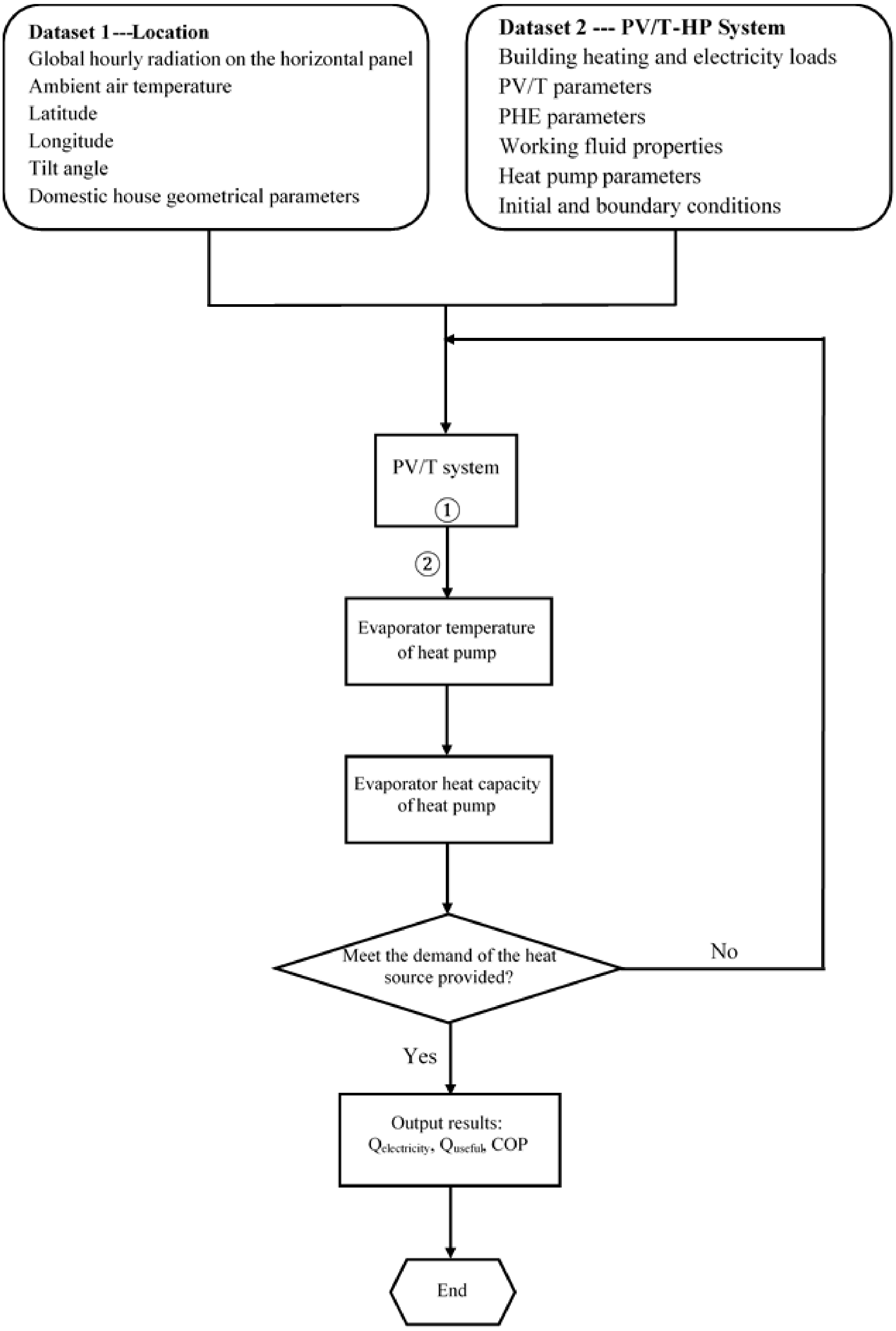
The differential and integral equations of the hybrid PV/T-HP system energy performance are developed based on finite difference method, which are solved by the Engineering Equation Solver (EES) commercial software package [50]. The flow chart of the solution procedure is given in Fig. 6 (a), and the subprogram of the computational process of the PV/T model is displayed in Fig. 6 (b).

The economic model is set up based on the Monte Carlo simulation by using the @RISK software [51]. Probability density function (PDF) is a statistical expression that defines a probability distribution (the likelihood of an outcome) for a discrete random variable as opposed to a continuous random variable. In order to establish the Monte Carlo model, an appropriate data range and a triangular distribution of each variable are defined as illustrated in Table 4. To be more specific, the ranges of the initial cost, electrical energy output, electricity price and thermal energy production are £9000 to £18000, 4500 kWh to 9000 kWh, £0.075/kWh to £0.22/kWh and 14500 kWh to 25000 kWh, respectively. Moreover, the values of A, B and C in Table 4 represent different inputs for the triangular distribution, A is the low end of the distribution, B is the peak value, and C is the high end of the distribution. In terms of constant inputs, the range represents the value used. The whole assessment is divided into six sections and the flow chart of LCC evaluation is depicted in Fig. 7. For all analyses presented in this work, a 2000 iteration Monte Carlo simulation is operated using the above equations, data ranges and distributions.

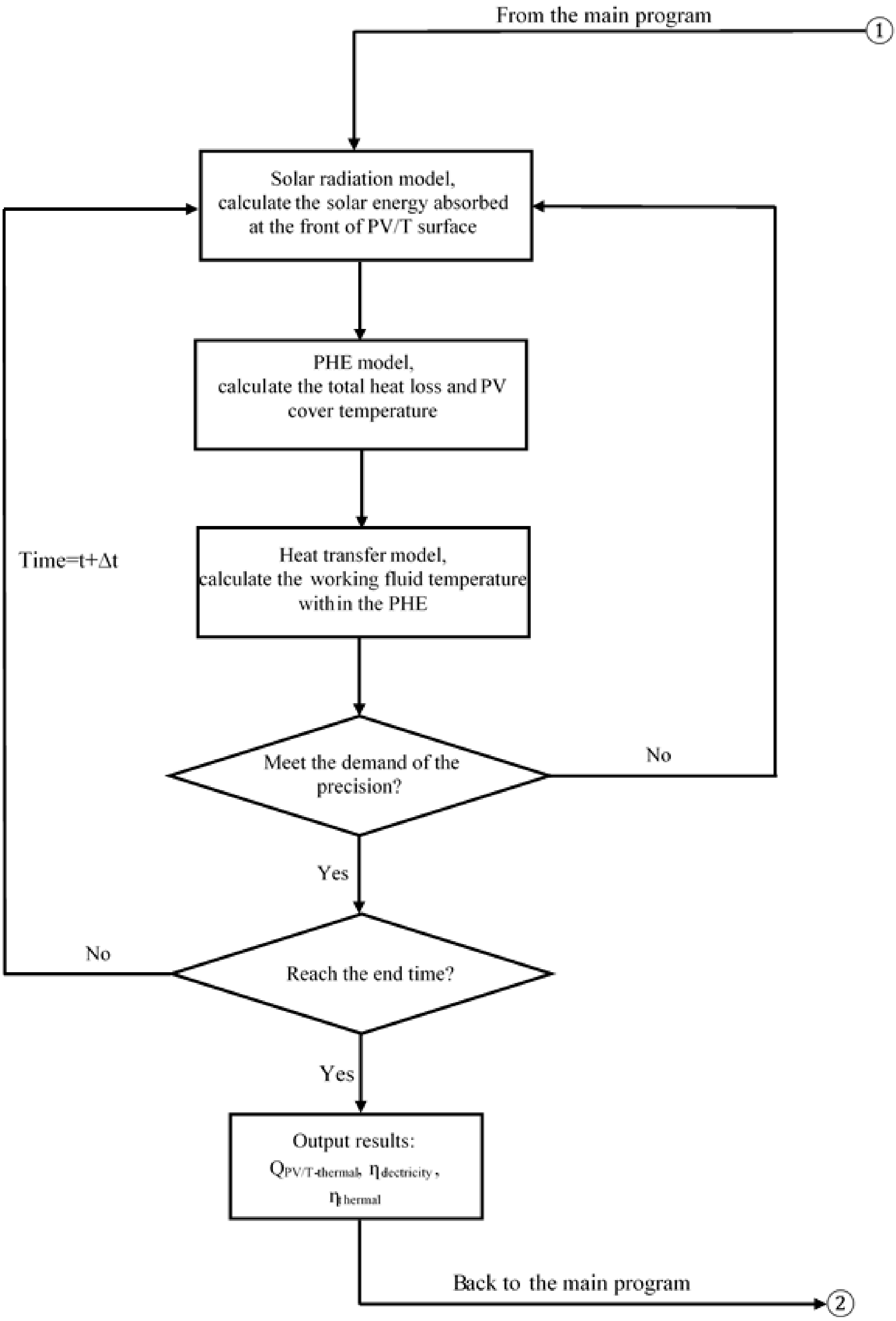
Table 4 Economic analysis input data of the PV/T-HP system

Items	Distribution	Range	A	B	C
Initial cost (£)	Triangular	9000-18000	9000	12015	~~15000~~18000
Electrical energy output (kWh)	Triangular	4500-9000	4500	7430	9000
Thermal energy output (kWh)	Triangular	14500-25000	14500	23833	25000
Annual interest rate (%)	Constant	7	-	-	-
Operating period (years)	Constant	25	-	-	-
System maintenance cost (£)	Triangular	140-180	140	160	180
Income tax rate (%)	Constant	20	-	-	-
Annual mortgage payment (£)	Constant	927.91	-	-	-

Electrical price (£/kWh)	Triangular	0.075-0.22	0.075	0.20	0.22
FIT (£/kWh)	Constant	0.1097	-	-	-
RHI (£/kWh)	Constant	0.0895	-	-	-
Heat rate (£/kWh)	-	-	-	-	-
Discounted rate (%)	Triangular	6.75-9.75	6.75	8.75	9.75
Deposit payment (%)	Triangular	8-15	8	10	15



(a)



(b)

Fig. 6. Flowchart of the computing procedure: (a) whole system; (b) PV/T subsystem

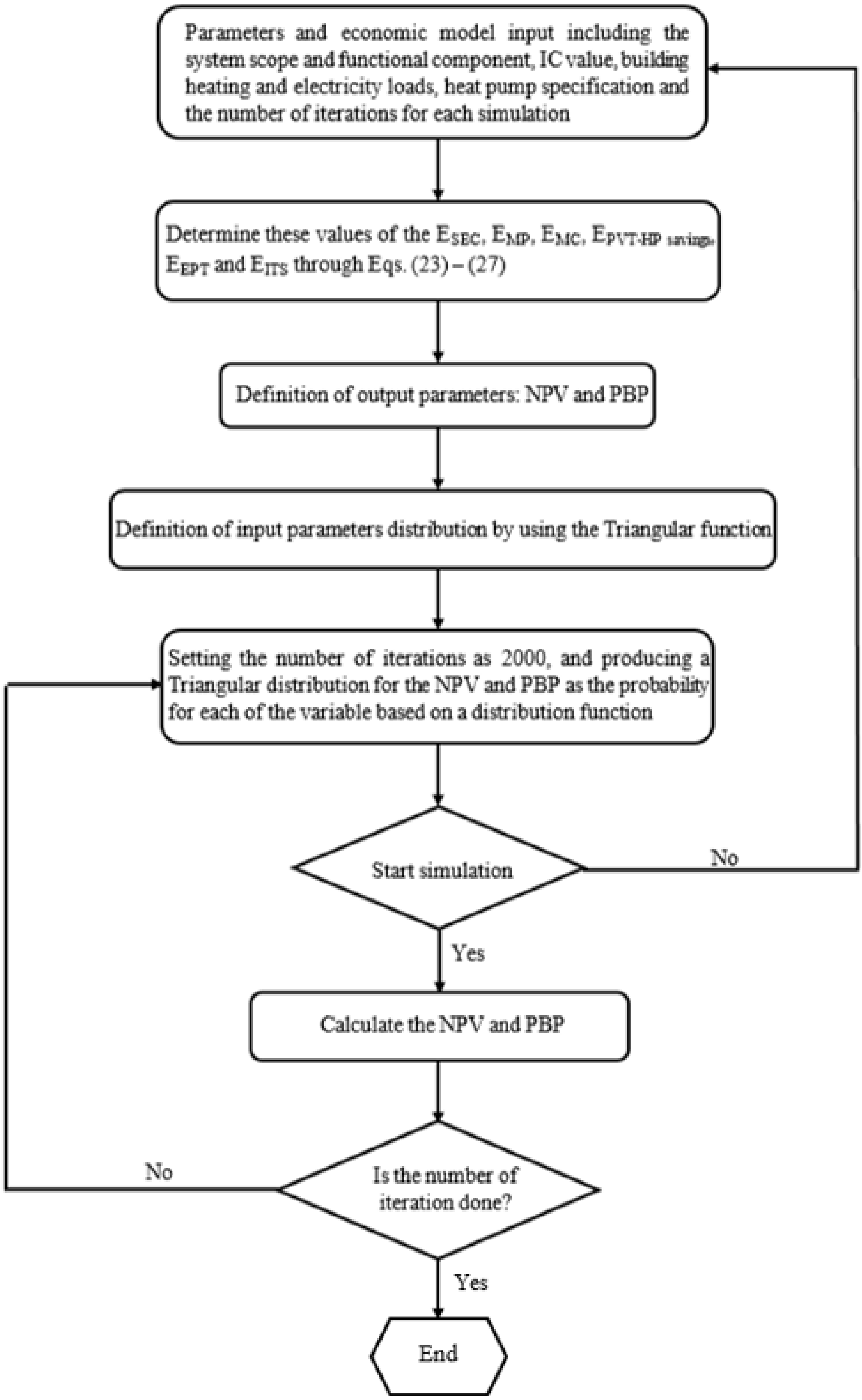


Fig. 7. The flowchart of economic evaluation for PV/T-HP system

4. Results and discussion

4.1 Energy performance

The investigated period of the PV/T-HP system is from 01st/May/2017 to 30th/April/2018, which is categorized into two stages based on the local weather condition. The first stage is from May to September with 8-hour daily operating time, another one is from October to April with 6-hour daily operating time. The PV array monthly average electricity generation and efficiency are shown in Fig. 8, the PV/T module thermal output and efficiency are presented in Fig. 9. According to Fig. 8, the maximum monthly electricity output is 981.57 kWh in June whereas the minimum is 298.42 kWh in December, with the corresponding electricity efficiencies of 15.52% and 10.95%, respectively. The annual electricity production is 7430.21 kWh with the mean electricity efficiency of 13.07%. It is found from Fig. 9 that the maximum monthly thermal energy output of the PV/T module is 1691.99 kWh in June while the minimum reaches 1220.44 kWh in December, with the corresponding thermal efficiencies of 30.10% and 8.80%, respectively. The total heat from the PV/T module is 17096.46 kWh per annum.

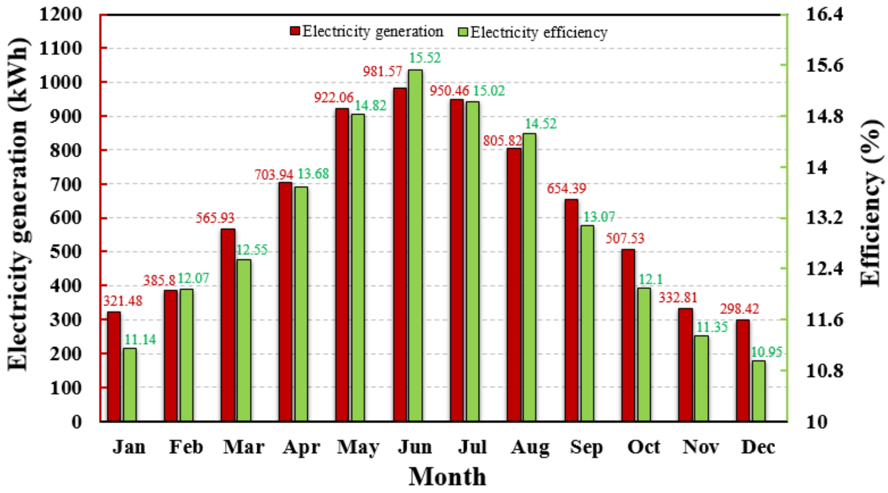


Fig. 8. Monthly PV electricity production and electricity efficiency

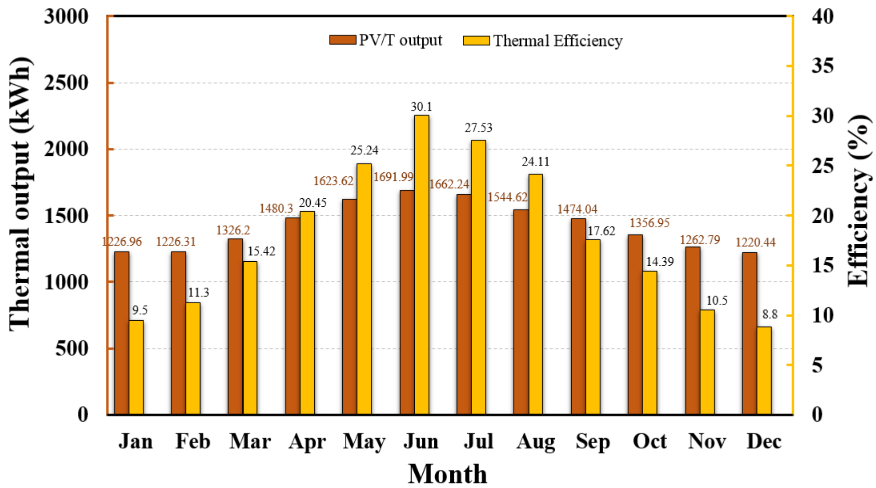


Fig. 9. Monthly PV/T thermal output and thermal efficiency

The building thermal energy demand, PV/T-HP thermal energy output and additional heat supplied are indicated in Fig. 10. The system highest monthly thermal energy output of 2486.35 kWh is achieved in June whereas the lowest is 1616.47 kWh in December. Moreover, the system thermal energy output is able to cover the building heat demand from April to October. Nevertheless, for November to March, the system thermal energy output cannot fulfil the heating requirements, so the additional heat is required for this period. The annual thermal energy output from the PV/T-HP is 23832.56 kWh whereas the building annual heating load is 22087 kWh, thereby, additional heat of 3497.49 kWh is required in this case.

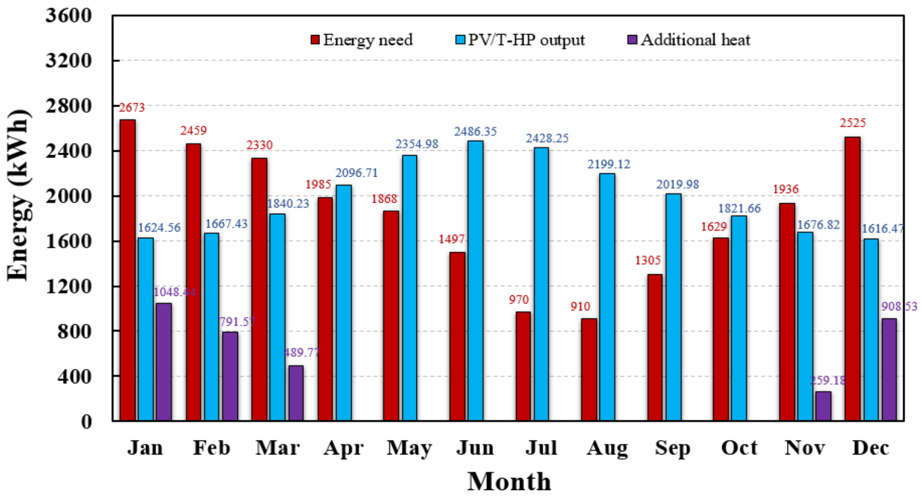


Fig. 10. Thermal energy demand, PV/T-HP output and additional heat supplied

The monthly average heat pump power consumption and COP are presented in Fig. 11. The maximum and minimum monthly electrical consumption are 794.36 kWh in June and 389.51 kWh in December, with the corresponding COPs of 3.13 and 4.15, respectively. The total electricity consumption of the heat pump is 6736.37 kWh per annum with a mean COP of 3.62.

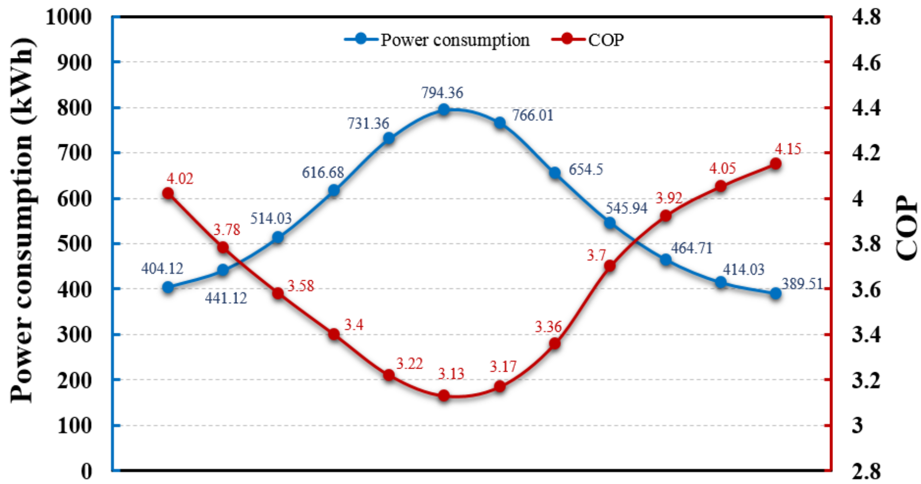


Fig. 11. Monthly heat pump power consumption and COP

As demonstrated in Fig. 12, the building electricity load including the household usage, circulation pump and heat pump consumption, is 10611.08 kWh per annum. In the meantime, the total electricity output of the PV arrays reaches 7430.21 kWh per annum. Specifically, for two periods from January to April and from September to December, the electricity output of

3770.30 kWh (1988.48 kWh + 1781.82 kWh) is not capable of meeting the building electricity demand of 7186.64 kWh (3729.35 kWh + 3457.29 kWh). This indicates that the additional power of 3416.34 kWh is needed to meet the building electricity requirement. By comparison, from May to August, the PV array electricity output of 3659.91 kWh exceeds the building need of 3430.44 kWh. This means that 229.47 kWh electricity is fed into the national grid at export tariff rate.

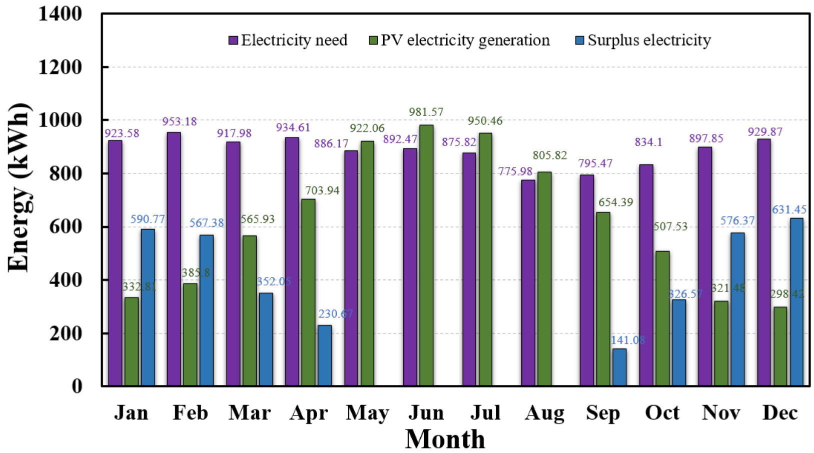


Fig. 12. Electricity demands, PV system electricity generation and surplus electricity supplied

4.2 Economic evaluation

4.2.1 Net present value and payback period

The annual progressions of the system energy and maintenance expenses for the 25-year lifetime service are illustrated in Appendix. It can be found that the PV/T-HP savings become positive reaching £2260~~.07~~ after the first year and reach £10329~~.40~~ until the 25th year. What is more, the system NPV is £38990~~.43~~ for the 25 years' running period. According to Fig. 13, the cash flow curve fluctuates at the 6th, 11st, 16th and 21st years because of the inverter replacement. Notably, the cash flow value becomes positive by the end of the 1st year as well as sustains positive consistently through the whole period of LCC assessment. The reason is that the system total energy output is high and the IC is relatively low, in the meantime, the system ME is low as well in this case.

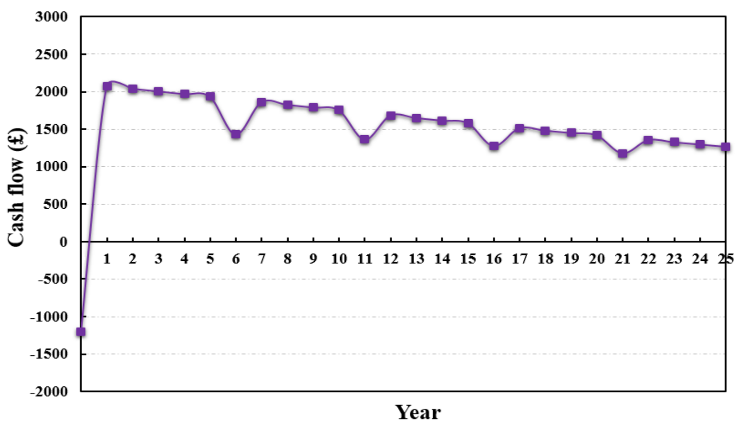


Fig. 13. The annual cash flow variation over the LCC analysis period

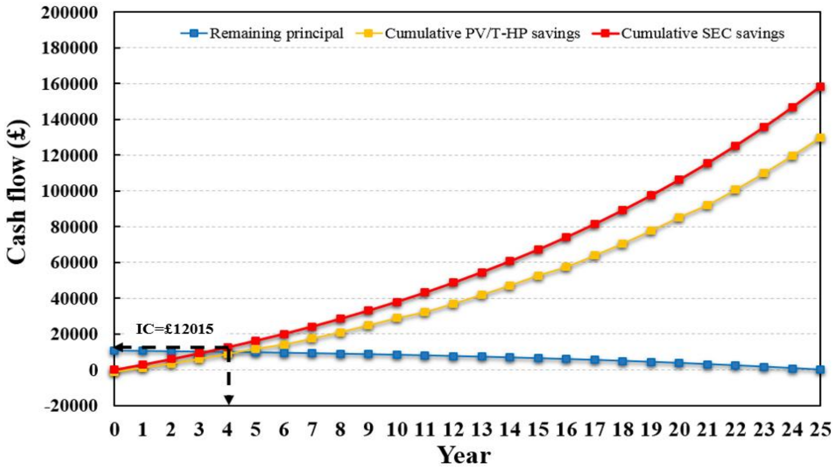


Fig. 14. Variation of remaining principle, cumulative PV/T-HP savings and cumulative SEC savings

It is found from Fig.14 that the cumulative SEC savings (£12639~~.48~~) surpass the IC (£12015) at the end of the 4th year. In the meantime, the cumulative PV/T-HP savings become positive after the 1st year owing to the relatively low IC and ME. The cumulative PV/T-HP savings (£11758~~.59~~) are in excess of the remaining principal balance (£9830~~.32~~) at the end of the 5th year. Furthermore, the PBP is 4.15 years as illustrated in Fig.14, this is regarded as an accredited PBP which is less than 10 years in terms of an engineering project in the UK context.

4.2.2 Sensitivity analyses

The sensitivity analyses are implemented in terms of the NPV and PBP to evaluate the sensitivities of the input variables by using the @Risk software. As shown in Figs. 15 and 16, the distribution bar charts demonstrate the probabilities against NPV and PBP for the PV/T-HP system during the entire life cycle period, respectively, the minimum, maximum, mean, standard deviations and number of iterations of the NPV and PBP are also indicated.

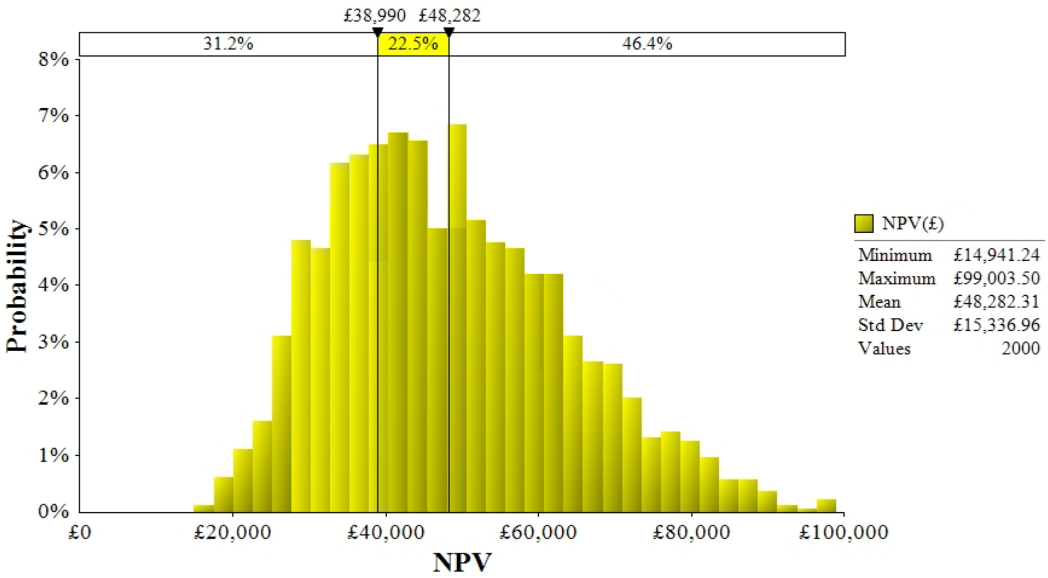


Fig. 15. Frequency prediction illustration of NPV

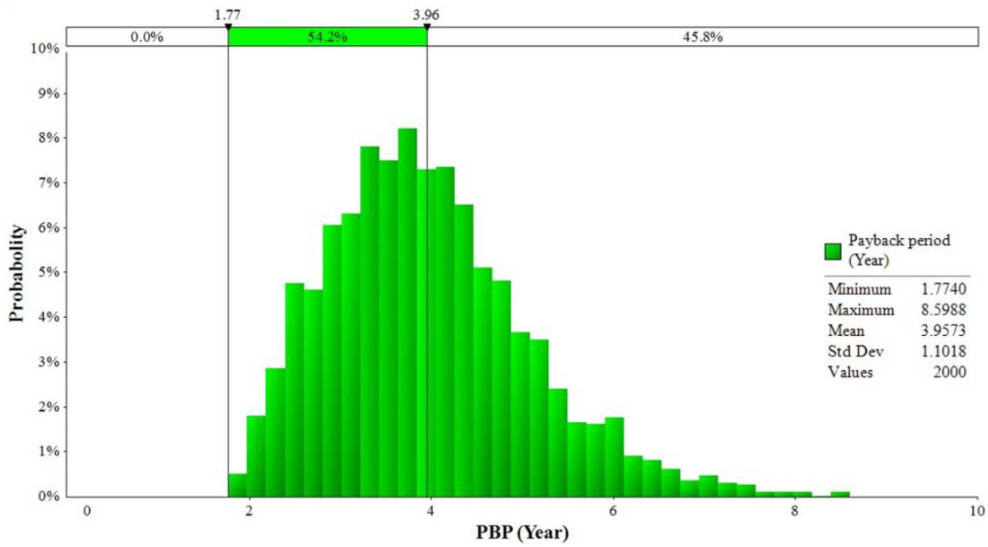


Fig. 16. Frequency prediction illustration of PBP

The vertical lines in Fig. 15 represent the NPV of present case (£38990) and average value (£48282~~.31~~). One row of percentages on the top of the diagram displays the probabilities relative to the NPV. Specifically, the top row depicts the probability regarding the LCC of the PV/T-HP system which is classified into three categories, it accounts for 31.2% when the NPV is less than the present case value; it makes up 22.5% when the NPV is located between the NPV of the present case value and average value; it accounts for a proportion of 46.4% when the NPV is greater than the average value. By contrast, the vertical lines in Fig. 16 denote the minimum (1.77 years) and average values (3.96 years) in the PBP. The top row of the graph, there is a probability of 45.8 % that the system PBP is more than 3.96 years, and 54.2 % of the payback time is between 1.77 and 3.96 years, while 0% of the payback period is less than 1.77 years.

The PV/T-HP system has the average NPV of £48282 after the 25-year running period, and there is nearly 22.5% possibility for this system to attain positive NPV (appreciated capital investment) between £38900 and £48282. By comparison, about 31.2% probability is lower than £38990 and 46.4% probability is higher than £48282. Based on the NPV decision-making regulation, the positive NPV illustrates that the capital investment on the presented system will be extremely cost-effective as the projected earning surpasses the expected expense. The average PBP is 3.97 years when the cash flow turns positive, as shown in Fig. 16. Similarly, there is 61.6% likelihood for the PV/T-HP system to attain a PBP less than 4.15 years, about 38.3% probability for the PBP is in the range of 4.15 to 8 years.

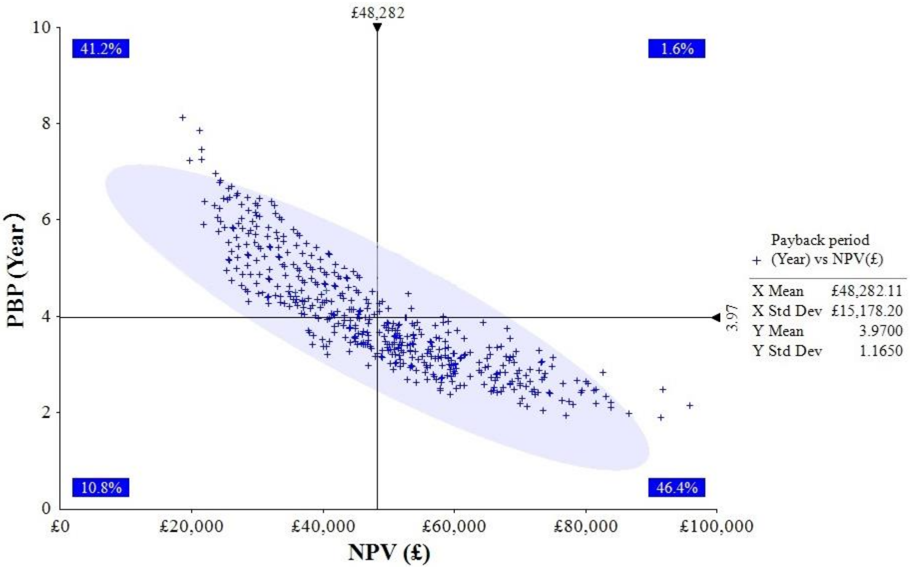


Fig. 17. NPV variation with PBP

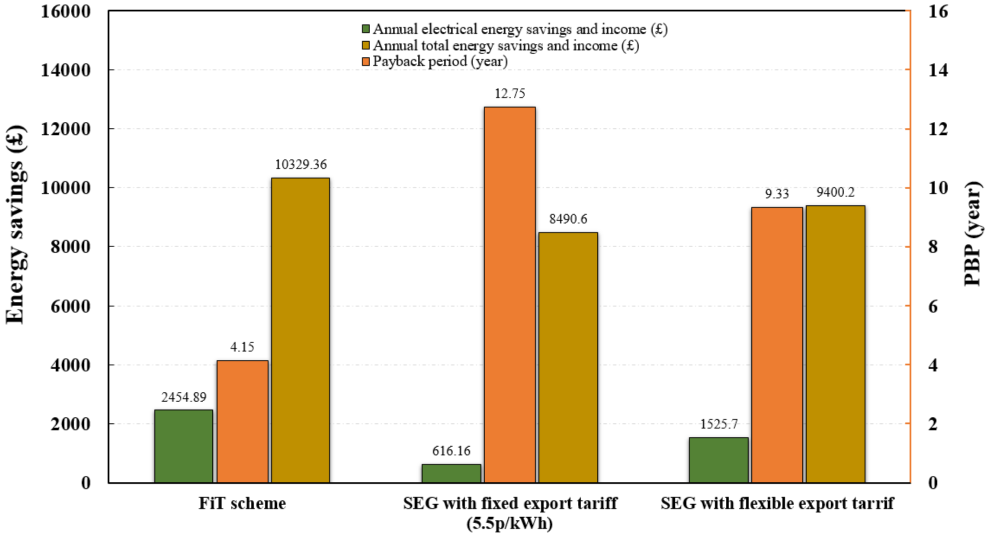
The PBP has a probability of 46.40 % to be less than a mean value of 3.97 years as the NPV is superior to a mean value of £48282, as shown in Fig. 17. There is only 1.60 % probability that the PBP can be over 3.97 years when the NPV is above the mean value. This indicates that the long PBP is unfavourable to the NPV. If the NPV is less than £48282, there is likelihood of 41.20 % that the PBP is higher than the average value, while only an opportunity of 10.80 % is for the low PBP value. This demonstrates that the higher NPV can be obtained when the shorter PBP is achieved in the study. The Monte Carlo simulation is able to define the average annuity and the stochastic fluctuation risk more precise, and show the system's economic stability. The methodology is in accordance with the previous studies in terms of NPV and PBP [36, 37, 52, 53].

4.4.3 Comparison between FiT and SEG schemes

The Feed-In Tariff (FiT) scheme is a UK government programme designed to promote the uptake of renewable and low-carbon electricity production technologies. It was introduced on 1st April 2010 and closed for the new entry on 31st March 2019 [54]. Though the FiT has come to an end, the extra electricity produced by solar panels will inevitably goes back to the grid and as under current legislation it would be illegal not to be paid. Therefore, the UK government (Department for Business, Energy & Industrial Strategy) launched a new replacement scheme, named the Smart Export Guarantee (SEG), and ensures that eligible small-scale, clean electricity generators will, under law, receive payments from electricity suppliers such as SSE, EDF Energy, British Gas, npower, Octopus Energy and Scottish Power (those with more than 250,000 electricity customers) for each unit of electricity they export to the grid [55, 56]. The new scheme was set on 9th June 2019 and mainly comes into force on 1st October 2019, which commences on 1st January 2020 [57].

Under the SEG, customers are only paid for the metered electricity they export back to their electricity suppliers. There is no longer a "generation tariff", so it is likely to take much longer before the capital investments are recovered by the SEG payments and energy savings [55, 56]. In comparison to the FiT scheme, the export price is not set by the UK government and there will be no long-term contracts. Based on this policy change, one of UK electricity suppliers like Octopus Energy has put forward two options with regard to the payments. One is a flat tariff called Fixed Outgoing Octopus that is a simple fixed payment for all surplus power exported to the grid at a fair market rate of 5.5p/kWh [58]. Another one is the flexible price called as Agile Outgoing Octopus that customers will get paid in the range from 4p/kWh to 9p/kWh at off peak time and from 10p/kWh to 15p/kWh at peak time [58]. This indicates that price changes at different time allow house owners generating renewable energy at home to taken into account the highly variable wholesale expense of energy throughout the day, and export at the most valuable times [58].

Based on new SEG policy, it can be observed from Fig. 18 that the annual electrical energy savings and income, under FiT, SEG with fixed export tariff and SEG with flexible export tariff schemes, can attain £2455~~4.89~~, £616~~.16~~ and £1526~~5.7~~, respectively. The FiT scheme could save approximately one time and twice as much costs in comparison to SEG with fixed export tariff and with flexible export tariff respectively. Similarly, the yearly energy savings and income under the FiT scheme is £10329~~.36~~ which is more than SEG with fixed export tariff of £8491~~0.63~~ and SEG with flexible export tariff of £9400~~.16~~. Furthermore, the PBP under the FiT scheme is 4.15 years which is far less than SEG with fixed export tariff of 12.75 years and SEG with flexible export tariff of 9.33 years.



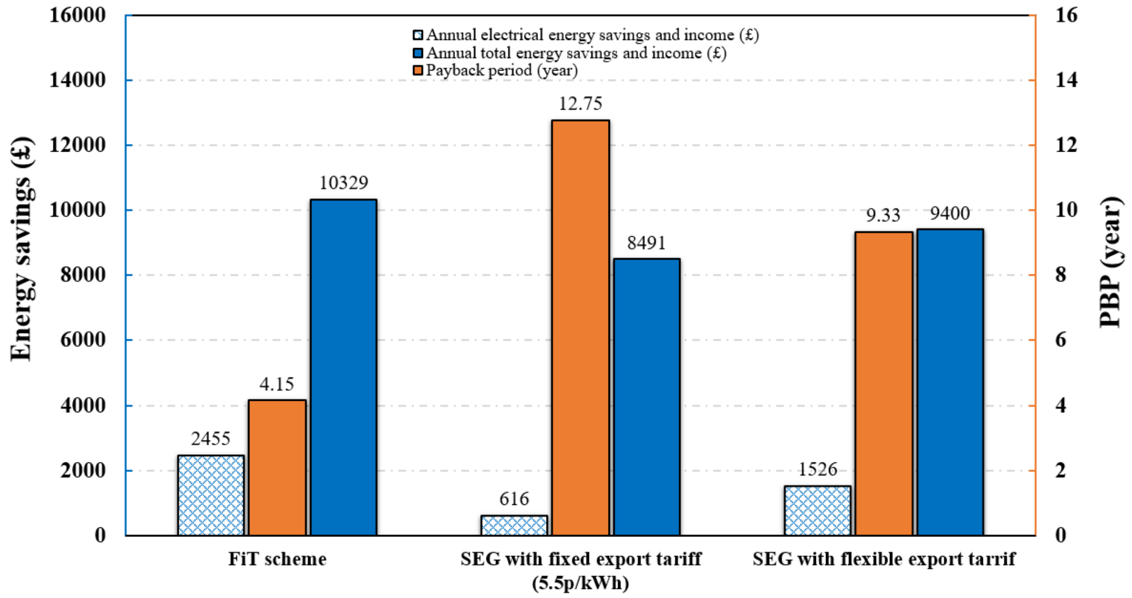


Fig. 18. Comparison of annual electrical energy savings and income, total energy savings and income and PBP between FiT and SEG schemes

The fact that there is no minimum to the export rate that energy companies must pay means that the government is envisaging a competitive market, but it will be difficult to make this happen artificially. That indicates that customers will likely experience very low export tariffs, much lower than with the FiT. That said, it is worth saying that this is a big step up from the previous government stance, no further subsidies of this nature would be thought until 2025. The SEG represents hope that the solar industry will not collapse entirely after the FiT has stopped taking new applications.

5. Conclusions

The energy performance and economic assessments of a hybrid PV/T-HP system are performed in this study. 18 CS6P-250P PV arrays with PHE are used in the PV/T module, and a 5.5 kW IVT Greenline heat pump is linked to the PHE to form the PV/T-HP system. The energy model of the PV/T-HP system is presented and used to evaluate its monthly electricity and heat generation, electricity consumption and COP via the EES software, the system economic model is set up through the Monte Carlo simulation which is solved using the @RISK software. A complete economic assessment is conducted considering the IC, ME, MP, SEC, EPT, ITS, PV/T-HP savings, NPV and cumulative savings, the sensitivity analyses of the NPV and PBP are also implemented. The key findings are concluded as follows:

- The PV/T-HP system could fulfil the building thermal and electrical demands from April to October and from May to August, respectively, and the extra electricity of 229.47 kWh is fed into the grid under the FiT scheme.
- The cumulative SEC savings (£12639~~.48~~) are in excess of the IC (£12015) at the end of the 4th year, the cumulative PV/T-HP savings (£11758~~.59~~) exceed the remaining of principal balance (£9830~~.32~~) at the end of the 5th year, and 4.15 years of the PBP is achieved.

- The PV/T-HP system with high NPV and short PBP has low initial investment.
- The Monte Carlo simulation is able to define the average annuity and the stochastic fluctuation risk more precise and thus enable a characterisation of the system's economic stability.
- The economic sensitive analyses reveal that the high discount rate reduces the system NPV whereas the high investment cost causes a long PBP to realize the positive NPV.
- Compared with the new SEG, the FiT is the most cost-effective scheme for renewable electricity generation and has the shortest PBP.

Appendix LCC of the PV/T-HP system for the domestic building in Nottingham throughout a 25-year operation period

Year	Energy generation (kWh/year)	SEC (£)	MP (£)	IP (£)	PP (£)	Principal balance (£)	Inverter replacement (£)	ME (£)	EPT (£)	ITS (£)	PV/T-HP savings (£)	Present worth of PV/T-HP savings (£)	Cum. PV/T-HP savings (£)	Cum. SEC savings (£)
0						10813.50					(1201.50)	(1201.50)	(1201.50)	
1	26338	2889.28	(927.91)	756.95	170.97	10642.53	–	(160)	(240.30)	699.01	2260.07	2078.23	1058.57	2889.28
2	26338	3062.64	(927.91)	744.98	182.93	10459.60	–	(167.20)	(249.91)	698.53	2416.15	2042.98	4315.95	5951.91
3	26338	3246.39	(927.91)	732.17	195.74	10263.86	–	(174.72)	(259.91)	697.97	2581.82	2007.42	6056.543	9198.31
4	26338	3441.18	(927.91)	718.47	209.44	10054.42	–	(182.59)	(270.30)	697.31	2757.69	1971.64	8814.23	12639.48
5	26338	3647.65	(927.91)	703.81	224.10	9830.32	–	(190.80)	(281.12)	696.54	2944.36	1935.73	11758.59	16287.13
6	26338	3866.51	(927.91)	688.12	239.79	9590.54	776.71	(199.39)	(292.36)	695.65	2365.79	1430.21	14124.38	20153.64
7	26338	4098.49	(927.91)	671.34	256.57	9333.96	–	(208.36)	(304.06)	694.64	3352.80	1863.82	17477.18	24252.14
8	26338	4344.41	(927.91)	653.38	274.53	9059.43	–	(217.74)	(316.22)	693.48	3576.02	1827.95	21053.2	28596.54
9	26338	4605.07	(927.91)	634.16	293.75	8765.68	–	(227.54)	(328.87)	692.16	3812.92	1792.23	24866.12	33201.61
10	26338	4881.38	(927.91)	613.59	314.31	8451.37	–	(237.78)	(342.02)	690.68	4064.35	1756.70	28930.46	38082.99
11	26338	5174.26	(927.91)	591.59	336.31	8115.05	900.42	(248.48)	(355.70)	689.02	3430.76	1363.54	32361.23	43257.25
12	26338	5484.71	(927.91)	568.05	359.86	7755.19	–	(259.66)	(369.93)	687.15	4614.37	1686.40	36975.60	48741.96
13	26338	5813.79	(927.91)	542.86	385.05	7370.15	–	(271.34)	(384.73)	685.07	4914.89	1651.71	41890.49	54555.76
14	26338	6162.62	(927.91)	515.91	411.99	6958.15	–	(283.55)	(400.12)	682.76	5233.81	1617.37	47124.30	60718.38
15	26338	6532.38	(927.91)	487.07	440.84	6517.31	–	(296.31)	(416.12)	680.19	5572.23	1583.39	52696.53	67250.76
16	26338	6924.32	(927.91)	456.21	471.69	6045.61	1043.84	(309.65)	(432.77)	677.35	4887.52	1277.09	57584.05	74175.09
17	26338	7339.78	(927.91)	423.19	504.72	5540.89	–	(323.58)	(450.08)	674.21	6312.43	1516.69	63896.47	81514.87
18	26338	7780.17	(927.91)	387.86	540.05	5000.85	–	(338.14)	(468.08)	670.75	6716.79	1484.00	70613.26	89295.04
19	26338	8246.98	(927.91)	350.06	577.85	4422.99	–	(353.36)	(486.80)	666.93	7145.84	1451.77	77759.10	97542.02
20	26338	8741.80	(927.91)	309.61	618.30	3804.69	–	(369.26)	(506.28)	662.73	7601.09	1420.01	85360.19	106283.80
21	26338	9266.31	(927.91)	266.33	661.58	3143.12	1210.09	(385.87)	(526.53)	658.13	6874.03	1180.86	92234.22	115550.10
22	26338	9822.29	(927.91)	220.01	707.89	2435.23	–	(403.24)	(547.59)	653.08	8596.63	1357.95	100830.80	125372.40
23	26338	10411.62	(927.91)	170.47	757.44	1677.78	–	(421.38)	(569.49)	647.55	9140.39	1327.67	109971.20	135784
24	26338	11036.32	(927.91)	117.44	810.47	867.32	–	(440.35)	(592.27)	641.49	9717.29	1297.91	119688.50	146820.40
25	26338	11698.50	(927.91)	60.71	867.19	0.12	–	(460.16)	(615.96)	634.89	10329.36	1268.65	130017.90	158518.90
Total												**38990.43**		

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Nomenclature

A	Area (m^2)
C_v	Clearance factor
D_H	Hydraulic dimeter (m)
d	Interest rate (%)
E	Expense (£)
f	Friction factor
Gr	Grashoff number
h	Heat transfer coefficient [W/(m·K)]
I	Incident solar radiation (W/m^2)
k	Discount rate (%)
L	PV panel length (m)
m	Mass flow rate (kg/s)
N	Number of time periods
Nu	Nusselt number
n	Polytropic compression coefficient
P	Pressure (k·Pa)
Q	Energy (kW)
T	Temperature (°C)

t	Time (s)
V	Wind speed (m/s)
V_c	Compressor swept volume (m^3)
W	Electricity consumption (kW)
x	Number of years before full recovery
Y	Number of mortgage payment years
y	Unrecovered cost at the start of the year (£)
Z	Principal payment (£)
z	Cash flow during the year (£)

Subscripts

absorber	Absorber
actual	Actual
air	Air
ave	Average
c	Glass cover
comp	Compressor
electricity	Electricity
fluid	Fluid
loss	Loss
pump	Circulation pump
r	Refrigerant
ref	PV module efficiency at reference temperature
s	Sky
thermal	Thermal
useful	Useful

Greek Letters

α	Absorptivity
β	Title-angle of PV panels
γ	PV cell temperature coefficient (°C^{-1})
ω	Compressor rotating speed (rev/s)
λ	Thermal conductivity of air (W/m·K)
ρ	Density (kg/m^3)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^2·K^4)
η	Efficiency (%)
τ	Transmittance
ε	Emissivity
ξ	Specific enthalpy (kJ/kg)
$\Delta\xi$	Specific enthalpy change (kJ/kg)

Abbreviations

AC	Alternating current
COP	Coefficient of performance
DC	Direct current
EES	Engineering equation solver
EP	Emissive power
ET	Export tariff
EVA	Ethylene vinyl acetate
FIT	Feed-in tariff
GHG	Greenhouse gas
IC	Initial cost
ITS	Income tax savings

LCC	Life cycle cost
LCOE	Levelized cost of energy
LCOH	Levelized cost of heat
ME	Maintenance expense
MP	Mortgage payment
NPV	Net present value
PBP	Payback period
PC	Periodic cost
PHE	Polyethylene heat exchanger
PP	Principle payment
PV	Photovoltaic
PV-HP	Photovoltaic with heat pump
PV/T-HP	Photovoltaic/thermal assisted heat pump
RHI	Renewable heat incentive
SEC	System energy cost
SEG	Smart Export Guarantee
SHP	Solar thermal with heat pump

Energy performance and life cycle cost assessments of a photovoltaic/thermal assisted heat pump system

Yuanlong Cui [a], Jie Zhu [b,*], Stamatis Zoras [a], Yaning Qiao [c], Xin Zhang [d]

[a] Department of Built Environment, College of Engineering and Technology, University of Derby, Derby, DE22 3AW, UK

[b] Department of Architecture and Built Environment, University of Nottingham, Nottingham, NG7 2RD, UK

[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, 221116, China

[d] School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK

Abstract

A photovoltaic/thermal module assisted heat pump system is investigated in this paper, which provides electrical and thermal energy for a domestic building. In-depth evaluation on the system energy production is conducted based on the finite difference method for a long-term operating period. The 25 years' system life cycle cost is assessed via the Monte Carlo simulation under the Feed-in Tariff (FiT) and Renewable Heat Incentive schemes, the annual energy savings, income and payback period (PBP) are compared for the FiT and Smart Export Guarantee (SEG) schemes. The technical analysis results illustrate that the system is able to fulfil the building thermal and electrical energy demands from April to October and from May to August, respectively, and the extra electricity of 229.47 kWh is fed into the grid. The economic assessment results clarify that the system achieves a net present value (NPV) of £38990 and has a PBP of 4.15 years. Meanwhile, the economic sensitive analyses reveal that the high discount rate reduces the system NPV whereas the high investment cost causes a long PBP to realize the positive NPV. Compared with the SEG scheme, the FiT is the most cost-effective method for renewable electricity generation and has the shortest PBP.

Keywords: PV/T-HP system, Thermal and electrical energy production, Monte Carlo simulation, Net Present Value, Payback Period

* Corresponding author. Tel: +44-115-8466141 Fax: +44-115-951315
E-mail address: jie.zhu@nottingham.ac.uk

1. Introduction

Climate change has an increasing negative impact on our planet [1] and leads to global warming and ozone layer depletion. The greenhouse gas from fossil fuel is widely recognised as the key contributor towards the climate change. Currently, the energy consumption in building sector makes up around 40% of the total energy usage in European, therefore enhancing energy efficiency and adopting renewable energy are becoming more significant in this sector [2, 3]. This paper presents an alternative measure to provide electrical and thermal energy for a domestic building by using a hybrid renewable energy system.

In the past several years, the solar electricity applications have been increased hugely based on photovoltaic (PV) technology [4, 5]. The mean efficiencies of mono-crystalline and poly-crystalline modules have been improved from 12% to 17% and from 10% to 16%, respectively. This denotes that merely less than 20% of received solar radiation could be transformed into electricity, whereas more than 80% of the received solar energy is dissipated [6, 7]. The PV panel efficiency could be increased by using active or passive cooling method [8, 9], many researchers employed air and water to cool the PV panel with the extracted heat for various purposes, and found that water is superior to air in terms of cooling effect [10,11].

In order to enhance PV panel efficiency and take full advantage of the residual heat, the PV and thermal technologies are combined to form a single knowledge called Photovoltaic/Thermal (PV/T) technology. This technology can simultaneously generate heat and electricity with high energy efficiency compared with the separated units. Many researches on the PV/T module have been reported. Bigorajski and Chwieduk [12] investigated the performance of a PV/T module for single family house in Poland, and found that during winter months electrical and thermal efficiencies of the PV/T module reach approximately 11-12% and 18-19%, respectively. Huang et al. [13] tested a PV/T module consisting of a pump, a 120-L storage tank and a 240-W poly-crystalline silicon collector, and discovered that the module electrical and thermal efficiencies could achieve 12.77% and 35.33%, respectively. Herrando et al. [14] established a mathematical model for the PV/T module to evaluate electricity and heat outputs for a three-bedroom terraced house in the UK, and concluded that 51% of electricity and 36% of space heating demands could be met by the PV/T module, resulting in an annual saving of 0.8 tons of carbon dioxide. Aste et al. [15] setup a numerical model of the PV/T module and assessed its precision via using experimental data in Italy, and obtained that the module mean daily electrical and thermal energy efficiencies could reach 6% and 25%, respectively. Bianchini et al. [16] investigated a commercial PV/T system to supply electrical and thermal energy for a residential building in the central area of Italy, and concluded that the system could produce approximately 1362 kWh electricity and up to 443 kWh heat annually. Ramos et al. [17] carried out an energy assessment of the PV/T modules for the domestic buildings in different European locations, and confirmed that the presented modules are able to cover 60% of heating need and almost 100% of electricity requirement of the households.

Currently, several researches on the PV/T hybrid system have also been implemented to enhance the system electrical and thermal energy production. Bellos and Tzivanidis [18] utilized PV/T panels to drive a heat pump system to investigate the system performance, and found that the daily power and heating generation are 5.13 kWh and 34.9 kWh, respectively. In the meantime, the average energy and exergy efficiencies achieve 8.80 % and 65.9%, respectively. Zhou et al. [19] developed a novel heat pump system by integrating photovoltaic and thermal panels for space heating under low solar radiation condition, and obtained that the average thermal and electrical efficiencies are 33.4% and 15.9%, respectively. The mean thermal efficiency of the thermal panels could reach 60.4%, the COP of the heat pump is 4.7. Cai et al [20] developed a dual source heat pump water heater where a direct expansion PV/T evaporator and an air source evaporator operate parallel to absorb heat from the solar radiation and ambient, respectively. It is found that when the solar irradiation increases from 100 W/m^2 to 300 W/m^2, the Coefficient of Performance (COP) of the hybrid system increases from 2.25 to 2.66. In addition, when the ambient temperature varies from 10 °C to 30 °C, the COP of the hybrid system rises by 18.22%. Vallati et al. [21] investigated a PV/T assisted heat pump to provide electricity for the water source heat pump and thermal energy for building space heating in Craow, Milan and Roma based on different climate conditions. Their results demonstrate that when thermal and electrical efficiencies of the PVT are set respectively to 0.6 and 0.15, the heating requirement can be covered by 47% for Cracow, 62% for Milan and 70% for Rome. Lu et al. [22] proposed a PV/T with heat pump system using vapour injection cycle to harvest thermal energy and electric power in cold winter. Their results reflect that the total generated heat and electricity of the system reach 23.68 kWh and 0.51 kWh, respectively. Moreover, the average thermal COP_{th} and PV/T COP_{PVT} values are 3.27 and 3.45, respectively. Xu et al. [23] developed a PV/T with heat pump (PV/T-HP) system in Nanjing, China, which could achieve a mean COP of 4.8 and an electrical efficiency of 17.5% on a sunny day. Wang et al. [24] designed a multi-function PV/T-HP system for domestic building application, and denoted that the system mean thermal efficiency is approximately 37% and the heat pump COP ranges from 2.5 to 3.2. Zhou et al. [25] investigated an innovative hybrid PV/T system with novel mini channel and a heat pump for space heating, and concluded that the hybrid system reaches the mean solar efficiency of 45.0% and average COP of 4.9. Chen et al. [26] performed a study numerically and experimentally on an innovative heat-pipe solar PV/T-HP system, and discovered that high ambient temperature, solar radiation and PV backboard absorptivity contribute to the heat pump COP improvement.

Most economic evaluations regarding the hybrid PV/T system concentrate on the fundamental indicators and are performed by the life cycle cost (LCC) assessment method, such as levelized cost of heat (LCOH), levelized cost of energy (LCOE), net present value (NPV) as well as simple/discounted payback period (PBP). Riggs et al. [27] conducted an economic analysis for an innovative hybrid PV/T module based on the LCOH approach in the United States, and concluded that the PV/T with waste heat recovery could increase the lowest LCOH. Bianchini et al. [16] compared a PV/T system with the separated flat plate solar collector and PV module by the LCOE approach, and confirmed that the PV/T system is more economical in comparison to the separated systems. Gu et al. [30] performed an economic study for the PV/T technology based on Monte Carlo method in Sweden, and found that the capital investment on the PV/T module could be profitable since the planned earnings exceed the expected expenses over the whole lifetime period. Meanwhile, according to their sensitivity analysis, the solar irradiance, heating price and debt to equity ratio have high impact on the module PBP which ranges from 6 to 10 years. Thygesen and Karlsson [31] investigated the economic benefits of a PV heat pump (PV-HP), a solar thermal heat pump (SHP) and a PV/T-HP system by using the NPV approach, and demonstrated that the PV-HP system is the most cost-effective and has the highest solar energy fraction in comparison to the SHP and PV/T-HP systems. Buker et al. [32] performed the LCC assessment for a PV/T module in the UK, and obtained that the NPV reaches €19456.14 with an 11-year PBP. Zhang et al. [33] carried out the PV/T-HP economic analyses in Stockholm, London and Madrid by means of the NPV and PBP methods, and found that the yearly running expenses could be saved €2051.4, €1667.0 and €2768.7 respectively in above three locations. Moreover, the PBPs of all three locations are less than 5 years. Herrando and Markides [34] undertook an economic investigation of a hybrid PV/T system for distributed power and hot water supplies in London, UK, and discovered that the PBP is in the range of 10 to 13 years, which depends on the variations of inflation and discounted rates.

For these studies, only a few researchers deliberated the present values of both costs and savings whereas the remaining only took into account the present value of cost. Also in most cases, LCOE, LCOH, NPV are only determined by point values for all inputs parameters, disregarding the integrated uncertainty for investment decision. These methods are restricted because they could not provide a sense of the likelihood of different outcomes, resulting in a certain disagreement in real case. By comparison, the Monte Carlo simulation is an effective approach to solve complex economic assessment, which is a comparatively simple and established technique for including uncertainty and risk in quantitative model. In the Monte Carlo model, a calculation is carried out many times (usually hundred to millions), and each time with a set of input parameters is selected randomly based on the pre-defined distributions for each estimation. For example, Meschede et al. [35] analysed the effects of probabilistic distributed factors on PV system performance for hotels by means of Monte Carlo simulation, and concluded that occupancy fluctuation and weather condition are sensitive to investment decision. Meanwhile, Monte Carlo simulation contributes to defining the average of the annuity more precisely and to rate the risk of fluctuating weather and occupancy better. Rezvani et al. [36] performed a techno-economic evaluation of solar water heaters in Australia based on Monte Carlo simulation, and revealed that the solar water heaters could provide better long-term economic viability significantly in comparison with traditional systems at moderate auxiliary energy consumptions. Gu et al. [37] implemented a techno-economic analysis of a solar PV/T concentrator in Sweden through Monte Carlo simulation, and found that the solar irradiance, local heating price, product capital price, discount rate and debt to equity ratio have significant effects on the decision-makings of long-term investment in building sector.

Even though this approach has been utilized in standalone PV, solar thermal and PV/T domains for several years, currently there are rarely economic assessments of hybrid PV/T-HP by using the Monte Carlo simulation. This paper therefore fills the research gap by providing in-depth techno-economic analysis of the hybrid PV/T-HP system for a long-term operation period. To be more specific, the 25 years' cumulative NPV of a hybrid PV/T-HP system for the domestic building application in the UK is studied by considering several vital parameters including the initial cost (IC), system energy cost (SEC), mortgage payment (MP), maintenance expense (ME), periodic cost (PC), system income tax savings (ITS) and present worth of money under the FiT and RHI schemes. The PBP is attained by the SEC and cumulative cash flows, the sensitivity analyses of economic model are achieved as well. Furthermore, the annual electrical energy savings, total energy savings and PBP are compared for the FiT and new Smart Export Guarantee (SEG) schemes.

2. Hybrid system energy and economic models

A hybrid PV/T-HP system is used to meet heat and electricity demands of a domestic building in this study. A basic design schematic of the system is illustrated in Fig. 1, it mainly comprises of a water-based glazed PV/T module employing a polyethylene heat exchanger (PHE), a water-to-water heat pump unit, an inverter, a hot water tank and a circulation pump. The PV/T module provides electricity for the heat pump and water pump and heat for the heat pump evaporator.

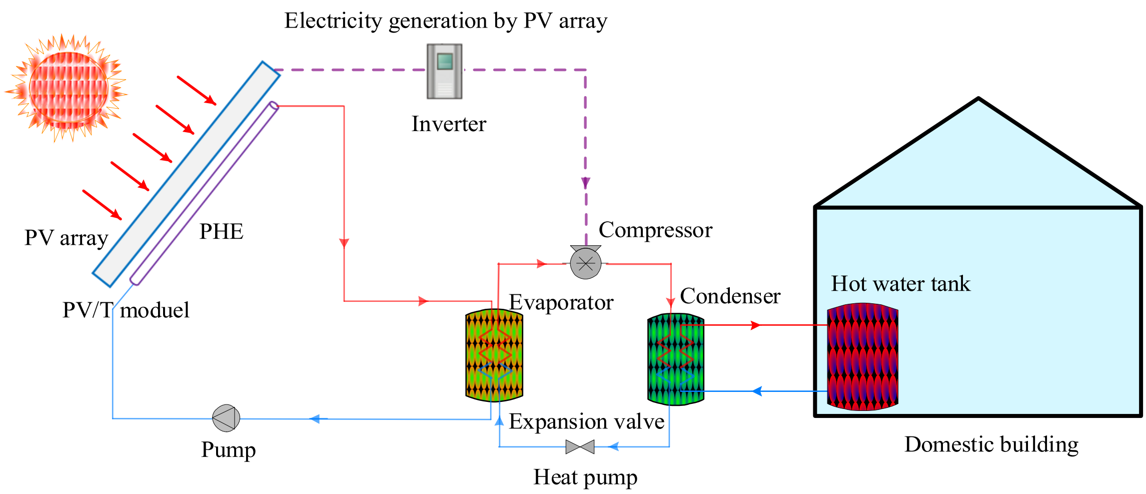


Fig. 1. The diagram of the PV/T-HP system applied in domestic building

2.1 Energy models

2.1.1 Photovoltaic/Thermal model

The PV/T module comprises of glass cover, PV array, ethylene-vinyl acetate (EVA) layer, PHE tube and adiabatic material layer. The solar cells are located in between two transparent tedlar-polyester-tedlar layers, and the EVA is placed behind the PV array. This forms a thermal conduction and electrical insulation structure, and the adiabatic material layer is set at the back of the PHE to minimize heat loss. A cross-sectional view of the PV/T module is given in Fig. 2. To be more specific, the solar radiation is transformed into electricity by PV array, meanwhile, thermal energy is absorbed by the working fluid within the PHE, and then passed to the heat pump evaporator.

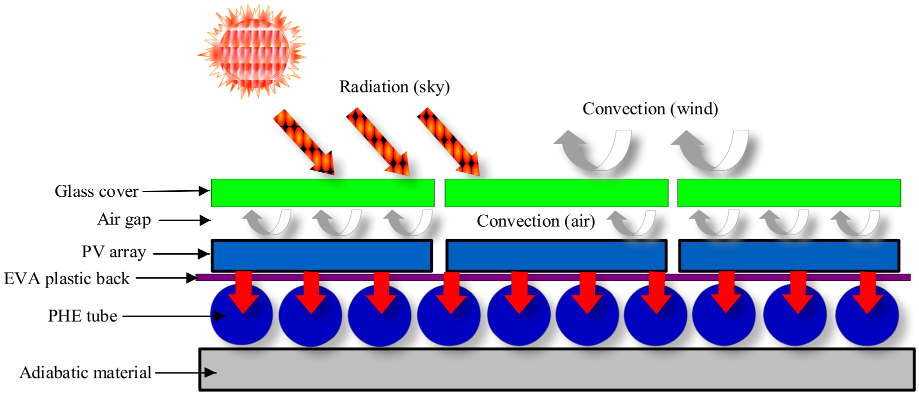


Fig. 2. A cross-sectional view of the PV/T module

In order to reduce the computing time and simplify the determination process, some assumptions are established as follows:

1) The module is at a quasi-steady state.
2) All material layers have homogeneous surface temperatures.
3) Heat loss across the piping system is ignored.
4) The air between the PHE tube and PV array is at the stagnant state.
5) Heat loss across the adiabatic material is negligible.

Therefore, the system energy conservation equation is given as:

$$\frac{\partial Q_{PV/T-thermal}}{\partial t} = Q_{absorber} - Q_{PV/T-loss} - Q_{electricity} \quad (1)$$

where $Q_{PV/T\text{-}thermal}$ is the useful thermal energy (kW); t is the time (s); $Q_{absorber}$ is the solar energy absorbed at the front of the PV/T surface (kW); $Q_{PV/T\text{-}loss}$ is the total heat loss (kW); $Q_{electricity}$ is the overall electricity output (kW).

$Q_{absorber}$ is calculated as follows:

$$Q_{absorber} = \tau_c \alpha_{absorber} A_{actual} I \quad (2)$$

where τ_c is the PV/T transmittance; $\alpha_{absorber}$ is the PV/T absorptivity ($\alpha_{absorber}$=0.9); A_{actual} is the PV/T actual area (m^2); I is the incident solar radiation (W/m^2).

The heat losses include the convection heat exchanges between the cover layer and ambient air ($Q_{conv,c,a}$), and between the EVA and PHE ($Q_{conv,\ EVA,\ PHE}$); the emissive powers (EP) between the cover layer and sky ($Q_{EP,c,\ sky}$), and between the EVA and PHE ($Q_{EP,EVA,PHE}$).

$$Q_{PV/T-loss} = Q_{conv,c,a} + Q_{EP,c,sky} + Q_{conv,EVA,PHE} + Q_{EP,EVA,PHE} \quad (3)$$

$$Q_{conv,c,a} = h_{conv}(T_c - T_a) \tag{4}$$

where h_{conv} is the forced convection coefficient of the ambient air, that can be approximated as a function of wind speed and given as [32, 38-40]:

$$h_{conv} = 5.7 + 3.8 \cdot V_{wind} \tag{5}$$

In order to get the glass cover temperature, the following empirical equation is adopted [38, 39]:

$$T_c = 30 + 0.0175 \times (I - 300) + 1.14 \times (T_a - 25) \tag{6}$$

where V_{wind} is the wind velocity (m/s); T_c is the PV cover temperature (°C); T_a is the ambient air temperature (°C).

The EP between the cover layer and sky is given as:

$$Q_{EP,c,sky} = \varepsilon_c \cdot \sigma \cdot (T_c^4 - T_s^4) \tag{7}$$

where ε_c is the PV/T cover layer emissivity (ε_c =0.96); σ is the Stefan-Boltzmann's constant, $5.67\text{x}10^{-8}$ $W/m^2 \cdot K^4$; T_s is the sky temperature (°C).

The sky temperature is calculated via Swinbank's equation [38, 39]

$$T_s = 0.037536 \cdot T_a^{1.5} + 0.32 T_a \tag{8}$$

The convection heat exchange between the EVA and PHE is given as:

$$Q_{conv,EVA,PHE} = h_{air} \cdot (T_{EVA} - T_{PHE}) \tag{9}$$

where h_{air} is the natural convective heat transfer coefficient between the PV array and PHE ($W/m^2 \cdot K$); T_{EVA} is the EVA plastic layer temperature (°C); T_{PHE} is the PHE outer wall temperature (°C).

h_{air} is written as:

$$h_{air} = \frac{N_u \cdot \lambda_{air}}{\delta_{air}} \tag{10}$$

where λ_{air} is the air thermal conductivity (W/m·K); δ_{air} is the air gap between the PV layer and glass cover (m).

Nu is the Nusselt number as follows:

$$Nu = [0.06 - 0.017(\frac{\beta_s}{90})]Gr^{1/3} \tag{11}$$

where β_s is the title–angle of PV array; Gr is the Grashoff number as given [38, 39]:

$$Gr = \frac{g \cdot (T_{pl} - T_{heo}) \cdot \delta_{air}^3}{\nu_{air}^2 \cdot T_{air}} \tag{12}$$

Hence, the EP between the EVA and PHE is given as:

$$Q_{EP,EVA,PHE} = \varepsilon_{EVA} \cdot \sigma \cdot (T_{EVA}^4 - T_{PHE}^4) \tag{13}$$

where ε_{EVA} is the EVA plastic layer emissivity.

The PV electrical efficiency can be obtained based on the temperature function [38, 39]:

$$\eta_{electricity} = \eta_{ref}[1 - \gamma_p (T_{absorber} - T_{ref})] \tag{14}$$

where $\eta_{electricity}$ is the PV array electrical efficiency (%); η_{ref} is the PV array efficiency at reference temperature (%); γ_p is the PV cell temperature coefficient (γ_p= 0.035 °C^{-1}); $T_{absorber}$ is the absorber surface temperature (°C); T_{ref} is the reference temperature (°C).

The total electrical energy is written as:

$$Q_{electricity} = \eta_e A_{actual} I \tag{15}$$

The thermal efficiency of the PV/T module is expressed as:

$$\eta_{thermal} = \frac{Q_{PV/T-thermal}}{A_{actual} \cdot I} \tag{16}$$

where $\eta_{thermal}$ is the thermal efficiency (%).

2.1.2 Heat pump model

A mechanical heat pump is coupled with the PV/T module in this case. Based on the local weather condition, the heat pump is assumed to run for heating purpose. Considering the influence of the compressor rotational speed, its electricity consumption is illustrated [41]:

$$m_r = V_c \omega \rho_{r,suc} \cdot [1 + C_v (1 - \frac{P_{r,cond}}{P_{r,evap}})^{\frac{1}{n}}] \tag{17}$$

$$\Delta\xi_{comp} = \xi_{r,dis} - \xi_{r,suc} = \frac{n}{n-1} \cdot \frac{P_{r,evap}}{\rho_{r,suc}} \cdot [(\frac{P_{r,cond}}{P_{r,evap}})^{\frac{n-1}{n}} - 1] \tag{18}$$

$$W_{comp} = \frac{m_r \Delta\xi_{comp}}{\eta_{comp}} \tag{19}$$

where m_r is the refrigerant mass flow rate (kg/s); ω is the compressor rotating speed (rev/s); V_c is the compressor suction volume (m^3); $\rho_{r,suc}$ is the compressor inlet working fluid density (kg/m^3); C_v is the clearance factor; P is the pressure (kPa); n is the refrigerant polytropic compression coefficient; ξ is the specific enthalpy (kJ/kg); Δξ is the specific enthalpy change (kJ/kg); η_{comp} is the compressor overall efficiency (%); W_{comp} is the compressor electricity consumption (kW).

The pressure drop of the working fluid within the PV/T module is determined through the friction factor (f) in the Darcy Weisbach equation [39], and expressed as:

$$\Delta p = f \frac{L}{D_H} \frac{\rho_{fluid} V_{fluid}^2}{2} \tag{20}$$

where L is the length of the PV array (m); D_H is the PHE tube hydraulic dimeter (m); ρ_{fluid} is the working fluid density (kg/m^3); V_{fluid} is the working fluid velocity in PV/T module (m/s).

The circulation pump electricity consumption is obtained by:

$$W_{pump} = \frac{\Delta p \times m_{pump}}{\rho_{fluid}\eta_{pump} / 100} \tag{21}$$

where η_{pump} is the pump efficiency (%); m_{pump} is the mass flow rate (kg/s).

2.1.3 Heat pump performance

The system useful heat (Q_{useful}) is equal to ($Q_{PV/T\text{-}thermal} + W_{comp} + W_{pump}$). Furthermore, the COP in heating mode is given as:

$$COP = \frac{Q_{useful}}{W} = \frac{Q_{PV/T-thermal} + W_{comp} + W_{pump}}{W_{comp} + W_{pump}} \tag{22}$$

2.2 Economic model

Economic policies have significant influence on the LCC assessment for the hybrid PV/T-HP system, such as tariff structure, fossil fuel penalty and renewable subsidy. The subsidy comes in different forms including investment rebate, Feed-in Tariff (FiT) and Export Tariff (ET) for renewable electricity and Renewable Heat Incentive (RHI) for renewable heat production. To obtain the accurate LCC evaluation results, the system boundary should be identified at first, which includes its scope and lifetime. The scope of the PV/T-HP system comprises of the PHE, PV array, inverter, heat pump and piping system. The lifetime of the PV/T-HP system is about 25 years [27, 32, 33, 37], which is adopted in this case as well. The inverter has a 5-year manufacturer warranty and is anticipated to be replaced at the end of each 5-year period. Based on the international standard of environmental management BS ISO 15686 [42], the LCC is the total expense of the PV/T-HP system in all stages from manufacture to disposal, and involves initial cost (IC), maintenance expense (ME), mortgage payment (MP), periodic costs (PC), system energy cost (SEC) and income tax savings (ITS) [37, 39].

To be more specific, the MP is a monthly payment made to pay back a mortgage, which consists of principal payment and interest of money on the loan borrowed for system installation [43, 44]. The principal portion is used to pay off the original loan whereas the interest is paid to the lender. For the property in this paper, it means that the system costs for the PV/T modules, inverter, PHE, ground pipes, water pump, heat pump, refrigerant and labour, are borrowed from a bank. Moreover, the PC are also known as periodic fixed costs. To keep the system in operating condition, some periodic costs, such as operation and maintenance costs, need to be paid. The PC denote the replacement costs of main system parts. For the hybrid PV/T-HP system, the inverter used in the system needs to be replaced after certain period of time, this cost is much more expensive compared with the annual maintenance fee. Basically, it is expected to be replaced at the end of each 5-year period [32, 40]. The heat pump is required to be replaced every 20 years [45]. Furthermore, the SEC is also known as the fuel cost saving, which is the total cost of household electricity and heat demands. The LCC of the PV/T-HP system is expressed as follows:

$$LCC = E_{IC} + \sum_{i=1}^{n}(E_{SEC} + E_{MP} + E_{ME} + E_{PC} + E_{ITS}) \tag{23}$$

where LCC is the system lifespan expense (£); E_{IC} is the initial cost including construction and engineering design expenses (£); E_{SEC} is the system energy cost in present worth (£); E_{MP} is the yearly mortgage payment in present worth (£); E_{ME} is the system maintenance expense in present worth (£); E_{PC} is the system periodic cost in present worth (£); E_{ITS} is the system income tax savings in present worth (£).

The MP composes of the principal payment (PP) and interest payment (IP), which can be given as:

$$E_{MP} = Z \times \frac{d_{MP} \cdot (1+d_{MP})^{Y}}{(1+d_{MP})^{Y} - 1} \tag{24}$$

where Z is the PP (£); d_{MP} is the yearly interest rate (%); Y is the number of MP years.

To maintain the PV/T-HP system in good operating condition, some expenses for operation and maintenance are required. The $E_{PVT\text{-}HP\ savings}$ is defined as the annual net cash flow [38, 40]:

$$E_{PVT-HP\ savings} = E_{SEC} - E_{MP} - E_{ME} - E_{PC} - E_{EPT} + E_{ITS} + E_{RHI} + E_{FIT} + E_{ET} \tag{25}$$

where E_{ET} is the Export Tariff that is paid for any surplus electricity sold to the grid.

The ITS of the PV/T-HP system can be expressed as [38, 40]:

$$E_{ITS} = E_{ETR} \times (E_{MP} + E_{EPT}) \tag{26}$$

where E_{ETR} is the effective tax rate (%); E_{EPT} is the extra property tax (£).

In this study, the NPV is adopted to assess a single investment whether is acceptable or not. The NPV is obtained by subtracting the present values of cash outflows (including initial investment) from the present values of cash inflows over the PV/T-HP life time. The higher the NPV, the higher the benefit. Thereby, the NPV is expressed as:

$$NPV = -E_{IC} + \sum_{N=1}^{N'} \frac{E_N}{(1+k)^N} \tag{27}$$

where E_N is the net cash inflow during the N period year (£); N is the number of time periods; k is the discount rate (%).

The PBP is given as:

$$PBP = x + \frac{y}{z} \tag{28}$$

where x is the number of years before full recovery; y is the unrecovered cost at the start of the year (£); z is the cash flow during the year (£). The PBP is utilized to calculate the period to recoup an investment, and it provides a more accurate indication by discounting each cash flow and considering the time value of money. What is more, the investment is considered financially viable if the payback time is lower than the expected lifetime of the investment.

3. Methodology

3.1 Domestic building

The selected domestic building, as shown in Fig. 3, is a detached house in Nottingham, UK, which is situated at 52.97° N and 1.10° W. It has four bedrooms with a total floor area of 134.64 m^2 and its roof area on the south side is 38.86 m^2. The building is designated for a family with 4 persons. Its main thermal energy is used for space heating and hot water whereas the electrical energy is used for fridge, washing machine, TV, computer, boiler, shower, lighting, cooker, microwave, dishwasher, etc.

Fig. 3. Location and photo of the detached house in Nottingham

3.2 Weather condition and energy demands

Meteorological data are essential for the accurate energy output of the hybrid PV/T-HP system and building energy load. The local mean ambient air temperature and solar radiation are presented in Fig. 4 [46]. The local highest mean temperature reaches 18.41 °C in August, while the lowest is 5.28 °C in January. Meanwhile, the monthly average solar radiation of Nottingham ranges from 14.79 kWh/m^2/month in December to 144.62 kWh/m^2/month in June [46]. The monthly average wind speed is in the range of 3.07 m/s to 4.49 m/s. The monthly building energy demands (thermal and electrical) are displayed in Fig. 5, which are obtained from the British Gas supplier. Specifically, the maximum and minimum thermal energy demands are 2673 kWh in January and 910 kWh in August, respectively. The largest electricity demand is 540.36 kWh in December whereas the smallest is 92.11 kWh in June. Furthermore, the building annual thermal and electrical energy demands reach 22087 kWh and 3874.71 kWh, respectively.

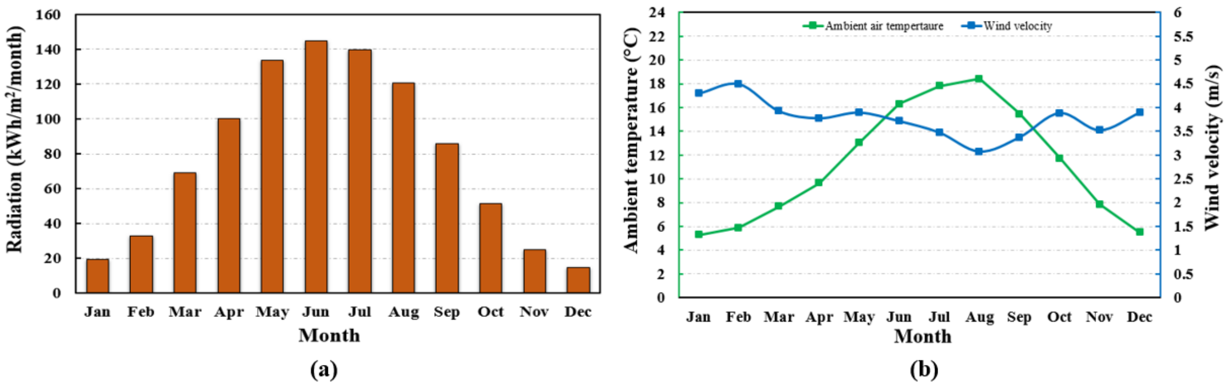


Fig. 4. Weather condition: (a) global irradiation; (b) wind velocity and ambient air temperature in Nottingham

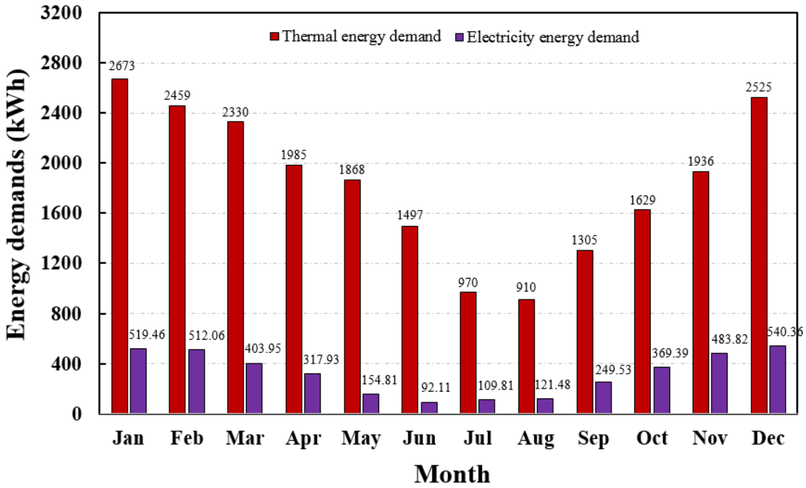


Fig. 5. Monthly building heat and electricity demands

3.3 System parameters

The design of the hybrid PV/T-HP system, specifically the determination of the component size in each application, is challenging because of a large number of factors involved, such as fluctuations in energy demand, uncertainties existing in renewable resources, precarious energy prices and complex interaction among components. Moreover, the PV/T performance depends on the location weather condition, and this must be accurately modelled for the optimal configuration to be achieved. Furthermore, the initial investment from the homeowner is a significant factor that requires to be considered during the whole design process. Therefore, 18 (250Wp) CS6P-250P photovoltaic solar arrays from Canadian solar company are utilized in the PV/T module based on the building electricity consumption, and installed at a 30° tilt angle oriented to the south. The arrays have anti-reflex coatings to increase the light absorption. The solar cell is polycrystalline silicon with the efficiency of 15.54% [47], and its operational temperature ranges from -40 °C to 85 °C. A 4.5 kW Afore HNS4500TL inverter is adopted to transform direct current (DC) into alternating current (AC). The PHE tube has the interior and exterior diameters of 0.0029 m and 0.0045 m, respectively. The water flow rate within the PHE is in the range of 2 L/min (0.12 m^3/hour) to 6 L/min (0.36

m^3/hour). Furthermore, the PHE is linked to a 5.5 kW IVT Greenline heat pump [45] that provides hot water at a temperature range from 35 °C to 65 °C. The technical details of the PV/T-HP system are shown in Table 1.

Table 1 Technical parameters of the PV/T-HP system [45, 47]

Component	Description	Value
CS6P-250P PV module	Module dimensions	1638 × 982 × 40 mm
	NO. of PV panels	18
	Cell type	Polycrystalline
	Packing factor	0.92
	Conversion efficiency	15.54%
	Nominal max. power	250 W
	Maximum current	8.30 A
	Maximum voltage	30.10 V
	Short circuit current	8.87 A
	Open circuit voltage	37.20 V
	Active total area	26.6 m^2
	Title angle	30°
	Manufacturer warranty	25 years
PHE module	The internal diameter of pipe	0.0029 m
	The external diameter of pipe	0.0045 m
	Spacing between PHE tubes	0.1 m
	Max temperature allowed in PHE	60 °C
	Max pressure allowed in PHE	1 MPa
	Mean mass flow rate	4.8 L/min
	Length	8 m
	Width	1 m
Heat pump	Emitted /Supplied output at 0/35°C	5.5/1.3 kW
	Refrigerant R407C mass flow rate	0.02 kg/s
	Operation temperature heat transfer system	-5 to 20 °C
	Nominal flow heating medium	0.30 l/s
	Minimum flow heating medium	0.20 l/s

3.4 Cost breakdown

The IC of the entire system is £12015 with 10% deposit, the rest of the IC is paid in a period of 25 years at an interest rate of 7%. The ME is assumed to be paid annually with an inflation rate of 4.5% [32]. The property tax is 2% of the initial investment whereas the ME for the PV/T-HP system is £120/year. The mean effective income tax rate (ITR) is estimated to be 20% during the LCC period. The ME and main installation expenses for the PV array, inverter, PHE, piping line and heat pump, are presented in Table 2, and the FIT, ET and RHI are considered as well in this study. According to the energy prices regulated by Office of gas and electricity markets [48] in the UK, the electricity price at FIT for homes is £0.1097/kWh whereas the electricity price at ET for supplying electricity into the grid is £0.052/kWh [48], the RHI for domestic building is £0.0895/kWh [49]. The detail component prices and economic parameters are displayed in Table 3.

Table 2 PV/T-HP system cost breakdown

Item	Value
PV/T	

PV arrays	£2273
Inverter	£670
PHE (×2)	£500
Pipe	£300
Pump (×1)	£45
Estimated PV/T unit cost	£3488
Heat pump	
Heat pump & commissioning	£5600
Refrigerant expense	£174
Estimated heat pump system expense	£5744
Other costs	
Header circuit insulation	£186
Brass fittings	£747
Estimated other equipment expense	£933
Labour costs	£1550
Total initial expense	£12015
Estimated maintenance expense	£120

Table 3 Parameters utilized for financial assessment

Item	Value
Electrical price	Feed-in tariff (building usage): £0.1097/kWh Export tariff (to the grid): £0.052/kWh
RHI for heat pump	£0.0895/kWh
Deposit payment	10%
Inflation rate of electricity price	6%
Interest rate of principal	7%
Inflation rate of maintenance	4.5%
Inflation rate of inverter price	3%
Council tax for property tax	2%
Inflation rate of extra property tax	4%
Income tax rate	20%
UK discount rate	8.75%

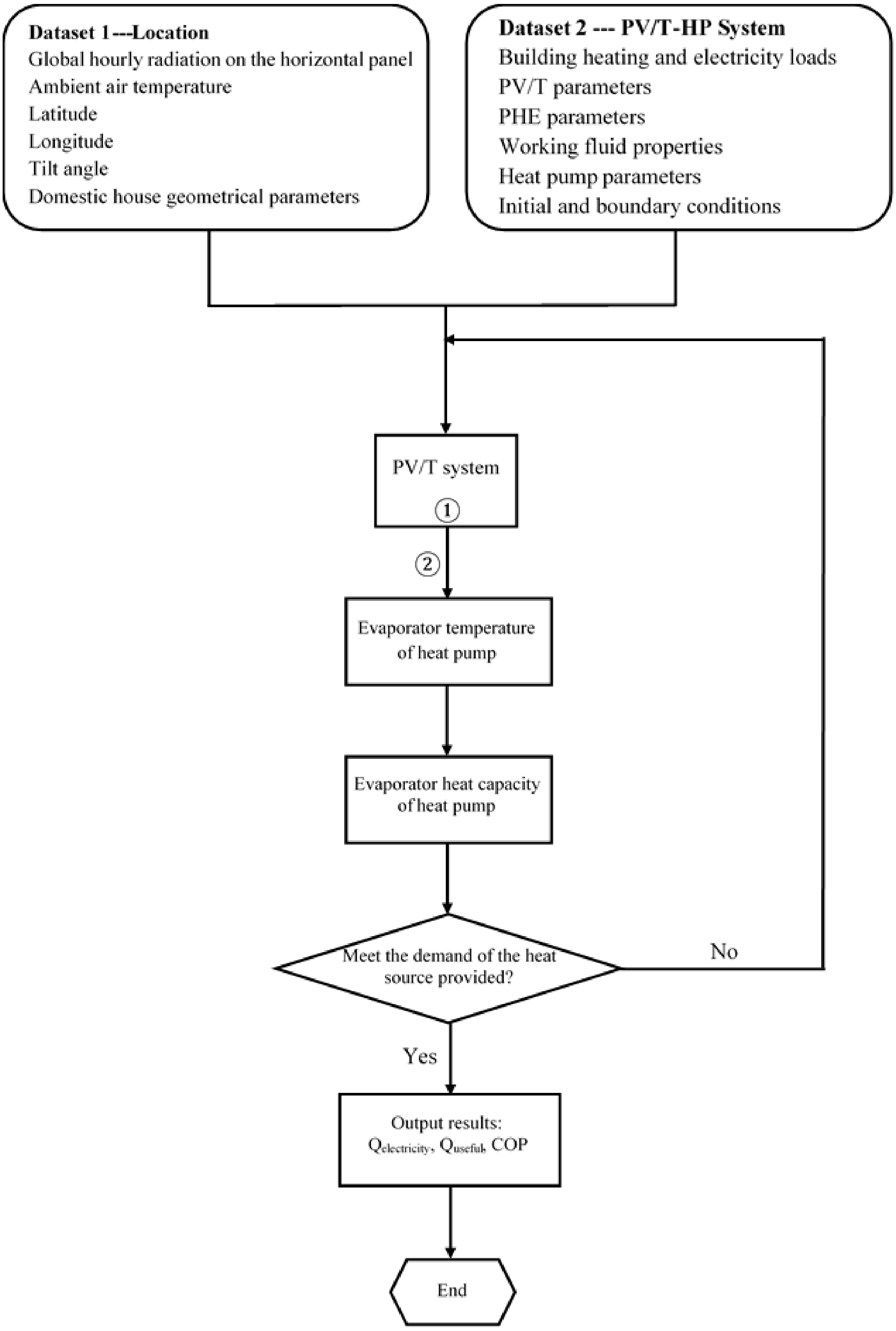
3.5 Program algorithm

The differential and integral equations of the hybrid PV/T-HP system energy performance are developed based on finite difference method, which are solved by the Engineering Equation Solver (EES) commercial software package [50]. The flow chart of the solution procedure is given in Fig. 6 (a), and the subprogram of the computational process of the PV/T model is displayed in Fig. 6 (b).

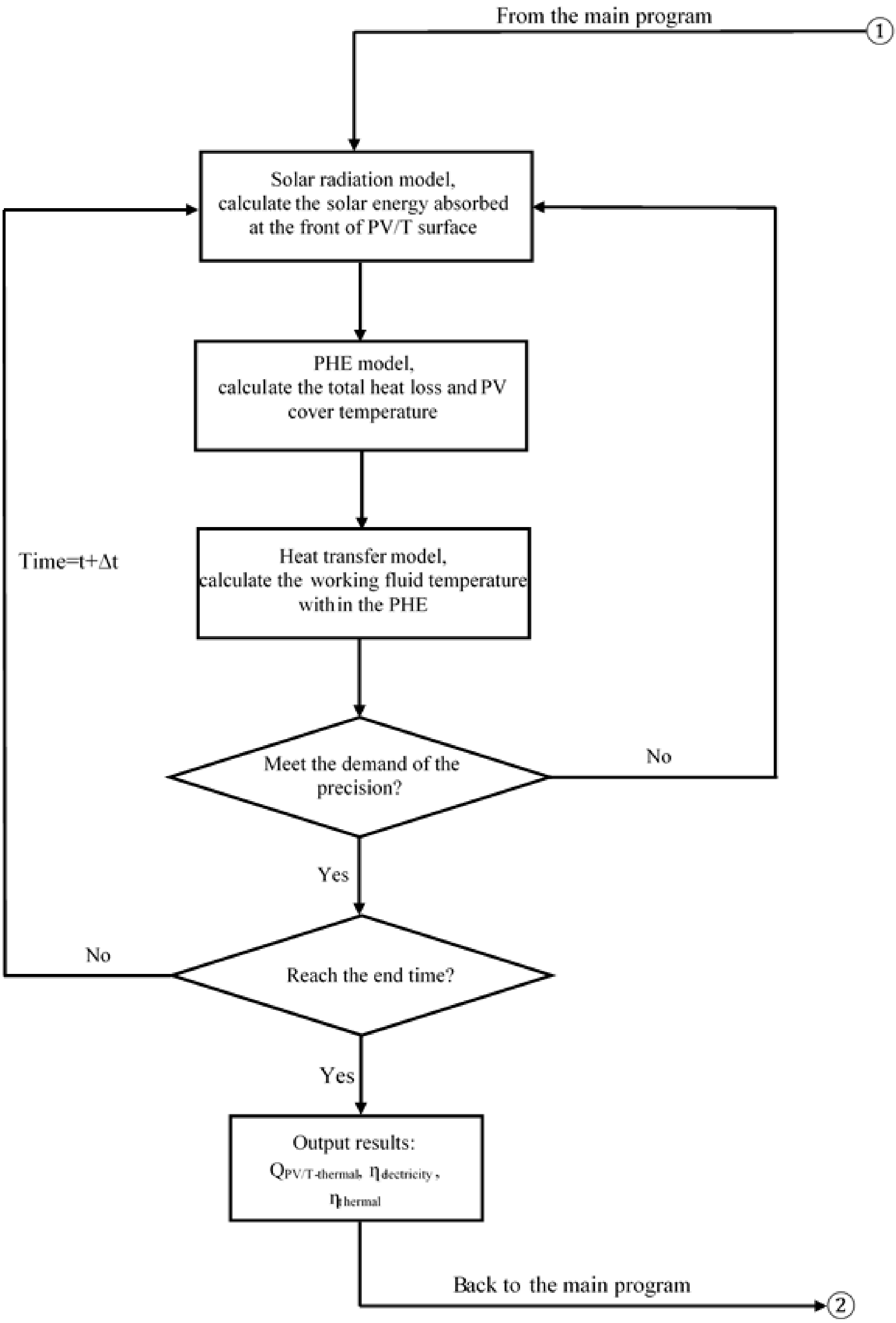
The economic model is set up based on the Monte Carlo simulation by using the @RISK software [51]. Probability density function (PDF) is a statistical expression that defines a probability distribution (the likelihood of an outcome) for a discrete random variable as opposed to a continuous random variable. In order to establish the Monte Carlo model, an appropriate data range and a triangular distribution of each variable are defined as illustrated in Table 4. To be more specific, the ranges of the initial cost, electrical energy output, electricity price and thermal energy production are £9000 to £18000, 4500 kWh to 9000 kWh, £0.075/kWh to £0.22/kWh and 14500 kWh to 25000 kWh, respectively. Moreover, the values of A, B and C in Table 4 represent different inputs for the triangular distribution, A is the low end of the distribution, B is the peak value, and C is the high end of the distribution. In terms of constant inputs, the range represents the value used. The whole assessment is divided into six sections and the flow chart of LCC evaluation is depicted in Fig. 7. For all analyses presented in this work, a 2000 iteration Monte Carlo simulation is operated using the above equations, data ranges and distributions.

Table 4 Economic analysis input data of the PV/T-HP system

Items	Distribution	Range	A	B	C
Initial cost (£)	Triangular	9000-18000	9000	12015	18000
Electrical energy output (kWh)	Triangular	4500-9000	4500	7430	9000
Thermal energy output (kWh)	Triangular	14500-25000	14500	23833	25000
Annual interest rate (%)	Constant	7	-	-	-
Operating period (years)	Constant	25	-	-	-
System maintenance cost (£)	Triangular	140-180	140	160	180
Income tax rate (%)	Constant	20	-	-	-
Annual mortgage payment (£)	Constant	927.91	-	-	-
Electrical price (£/kWh)	Triangular	0.075-0.22	0.075	0.20	0.22
FIT (£/kWh)	Constant	0.1097	-	-	-
RHI (£/kWh)	Constant	0.0895	-	-	-
Heat rate (£/kWh)	-	-	-	-	-
Discounted rate (%)	Triangular	6.75-9.75	6.75	8.75	9.75
Deposit payment (%)	Triangular	8-15	8	10	15


Dataset 1---Location
Global hourly radiation on the horizontal panel
Ambient air temperature
Latitude
Longitude
Tilt angle
Domestic house geometrical parameters
Dataset 2 --- PV/T-HP System
Building heating and electricity loads
PV/T parameters
PHE parameters
Working fluid properties
Heat pump parameters
Initial and boundary conditions
PV/T system
1
2
Evaporator temperature of heat pump
Evaporator heat capacity of heat pump
Meet the demand of the heat source provided?
No
Yes
Output results:
$Q_{electricity}$, Q_{useful}, COP
End

(a)



(b)

Fig. 6. Flowchart of the computing procedure: (a) whole system; (b) PV/T subsystem

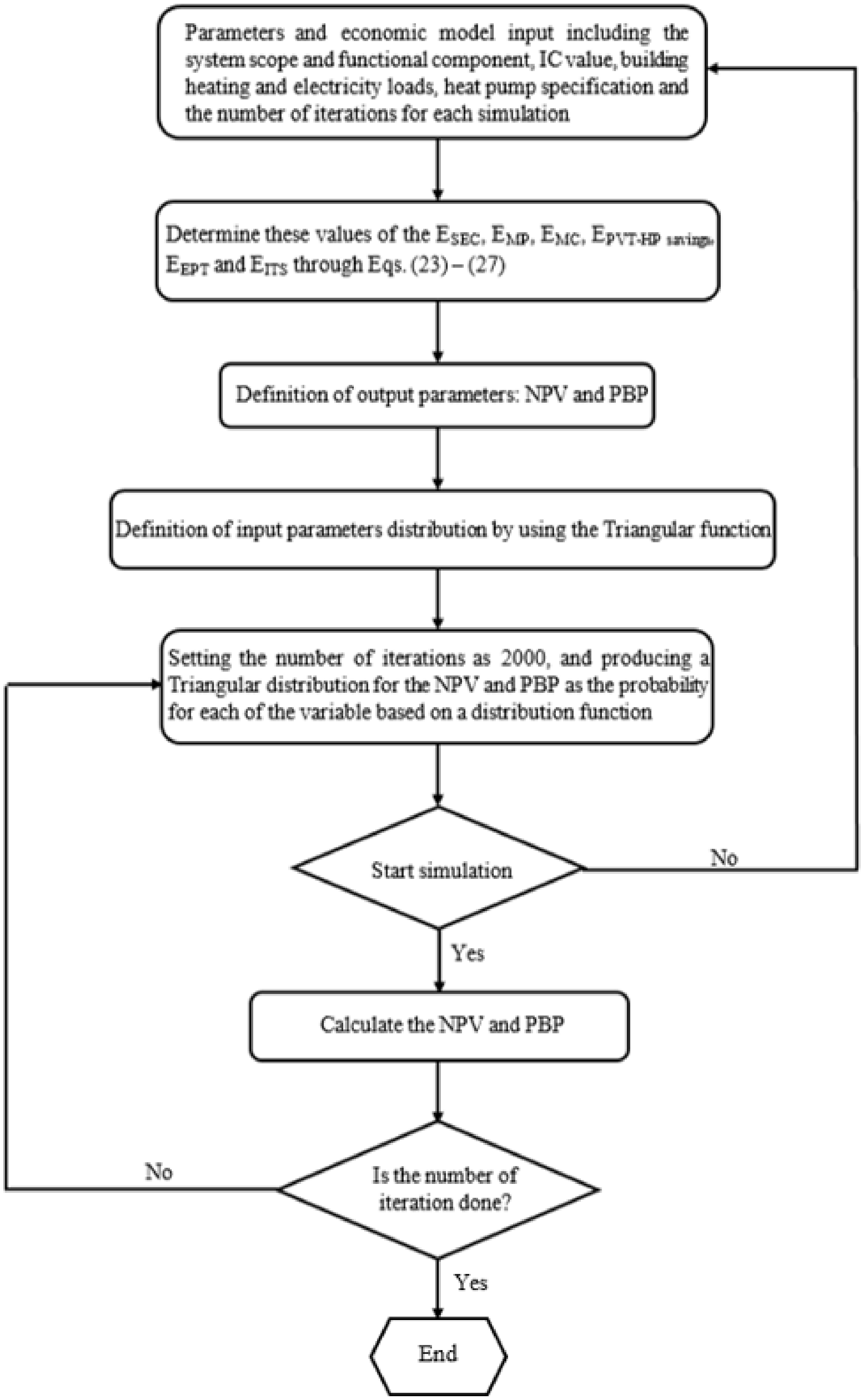


Fig. 7. The flowchart of economic evaluation for PV/T-HP system

4. Results and discussion

4.1 Energy performance

The investigated period of the PV/T-HP system is from 01st/May/2017 to 30th/April/2018, which is categorized into two stages based on the local weather condition. The first stage is from May to September with 8-hour daily operating time, another one is from October to April with 6-hour daily operating time. The PV array monthly average electricity generation and efficiency are shown in Fig. 8, the PV/T module thermal output and efficiency are presented in Fig. 9. According to Fig. 8, the maximum monthly electricity output is 981.57 kWh in June whereas the minimum is 298.42 kWh in December, with the corresponding electricity efficiencies of 15.52% and 10.95%, respectively. The annual electricity production is 7430.21 kWh with the mean electricity efficiency of 13.07%. It is found from Fig. 9 that the maximum monthly thermal energy output of the PV/T module is 1691.99 kWh in June while the minimum reaches 1220.44 kWh in December, with the corresponding thermal efficiencies of 30.10% and 8.80%, respectively. The total heat from the PV/T module is 17096.46 kWh per annum.

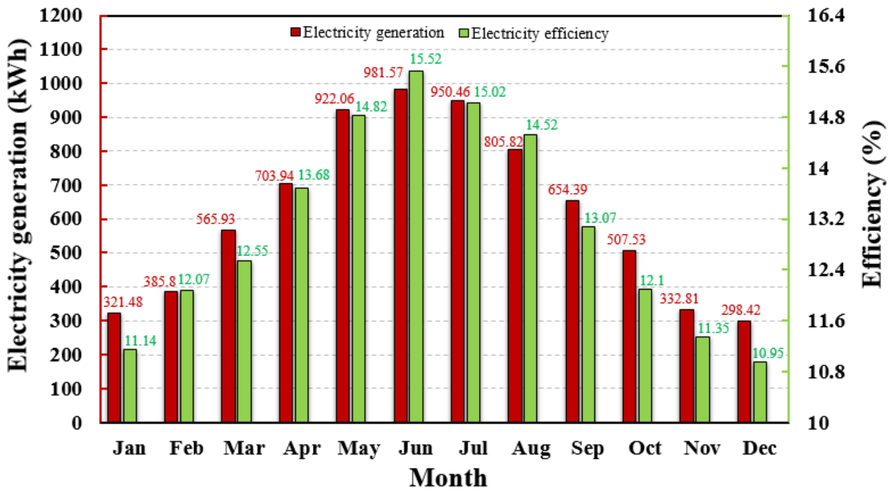


Fig. 8. Monthly PV electricity production and electricity efficiency

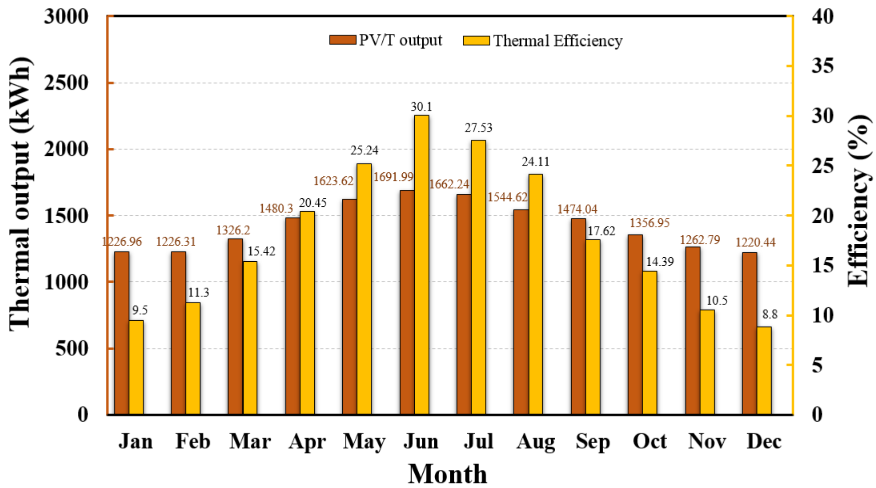


Fig. 9. Monthly PV/T thermal output and thermal efficiency

The building thermal energy demand, PV/T-HP thermal energy output and additional heat supplied are indicated in Fig. 10. The system highest monthly thermal energy output of 2486.35 kWh is achieved in June whereas the lowest is 1616.47 kWh in December. Moreover, the system thermal energy output is able to cover the building heat demand from April to October. Nevertheless, for November to March, the system thermal energy output cannot fulfil the heating requirements, so the additional heat is required for this period. The annual thermal energy output from the PV/T-HP is 23832.56 kWh whereas the building annual heating load is 22087 kWh, thereby, additional heat of 3497.49 kWh is required in this case.

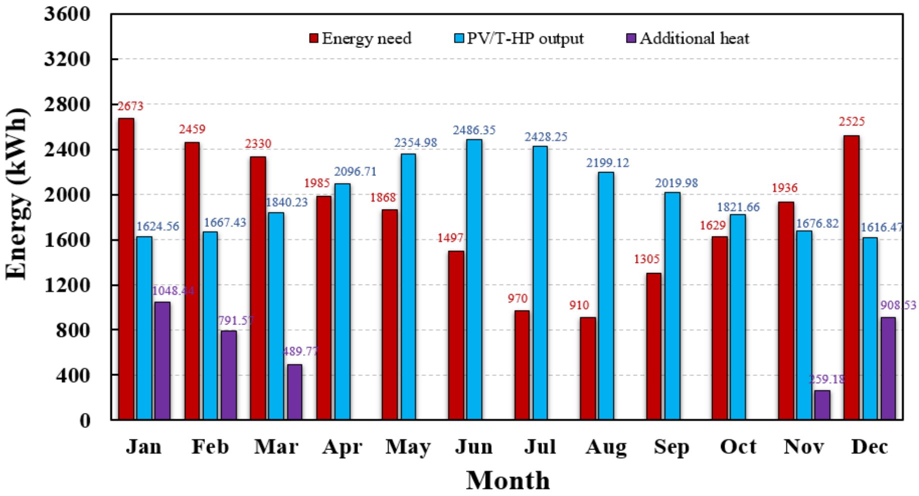


Fig. 10. Thermal energy demand, PV/T-HP output and additional heat supplied

The monthly average heat pump power consumption and COP are presented in Fig. 11. The maximum and minimum monthly electrical consumption are 794.36 kWh in June and 389.51 kWh in December, with the corresponding COPs of 3.13 and 4.15, respectively. The total electricity consumption of the heat pump is 6736.37 kWh per annum with a mean COP of 3.62.

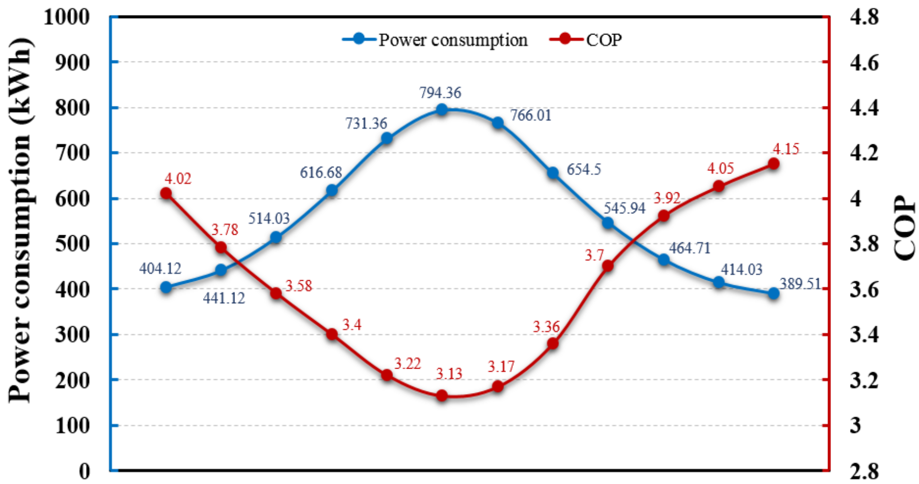


Fig. 11. Monthly heat pump power consumption and COP

As demonstrated in Fig. 12, the building electricity load including the household usage, circulation pump and heat pump consumption, is 10611.08 kWh per annum. In the meantime, the total electricity output of the PV arrays reaches 7430.21 kWh per annum. Specifically, for two periods from January to April and from September to December, the electricity output of

3770.30 kWh (1988.48 kWh + 1781.82 kWh) is not capable of meeting the building electricity demand of 7186.64 kWh (3729.35 kWh + 3457.29 kWh). This indicates that the additional power of 3416.34 kWh is needed to meet the building electricity requirement. By comparison, from May to August, the PV array electricity output of 3659.91 kWh exceeds the building need of 3430.44 kWh. This means that 229.47 kWh electricity is fed into the national grid at export tariff rate.

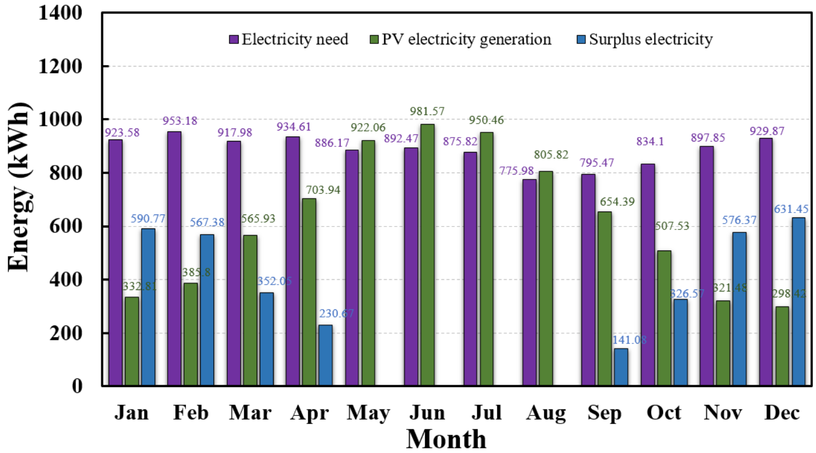


Fig. 12. Electricity demands, PV system electricity generation and surplus electricity supplied

4.2 Economic evaluation

4.2.1 Net present value and payback period

The annual progressions of the system energy and maintenance expenses for the 25-year lifetime service are illustrated in Appendix. It can be found that the PV/T-HP savings become positive reaching £2260 after the first year and reach £10329 until the 25th year. What is more, the system NPV is £38990 for the 25 years' running period. According to Fig. 13, the cash flow curve fluctuates at the 6th, 11st, 16th and 21st years because of the inverter replacement. Notably, the cash flow value becomes positive by the end of the 1st year as well as sustains positive consistently through the whole period of LCC assessment. The reason is that the system total energy output is high and the IC is relatively low, in the meantime, the system ME is low as well in this case.

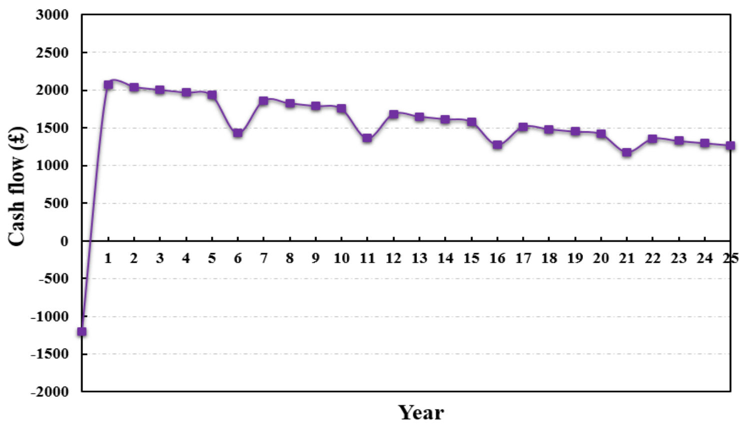


Fig. 13. The annual cash flow variation over the LCC analysis period

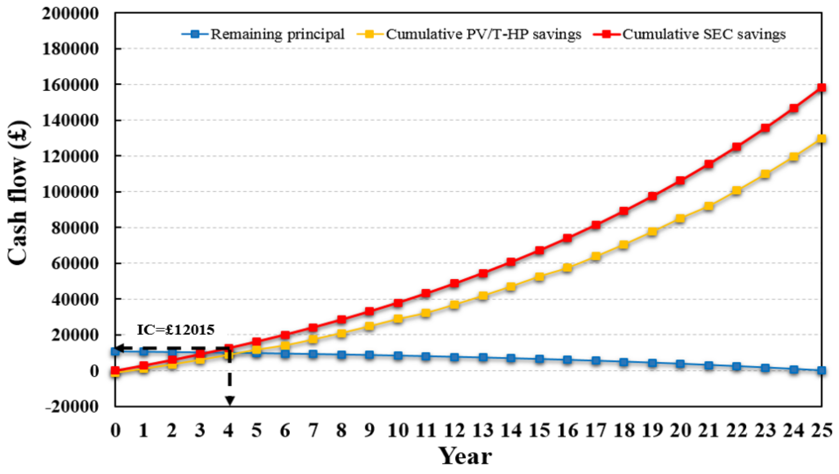


Fig. 14. Variation of remaining principle, cumulative PV/T-HP savings and cumulative SEC savings

It is found from Fig.14 that the cumulative SEC savings (£12639) surpass the IC (£12015) at the end of the 4th year. In the meantime, the cumulative PV/T-HP savings become positive after the 1st year owing to the relatively low IC and ME. The cumulative PV/T-HP savings (£11758) are in excess of the remaining principal balance (£9830) at the end of the 5th year. Furthermore, the PBP is 4.15 years as illustrated in Fig.14, this is regarded as an accredited PBP which is less than 10 years in terms of an engineering project in the UK context.

4.2.2 Sensitivity analyses

The sensitivity analyses are implemented in terms of the NPV and PBP to evaluate the sensitivities of the input variables by using the @Risk software. As shown in Figs. 15 and 16, the distribution bar charts demonstrate the probabilities against NPV and PBP for the PV/T-HP system during the entire life cycle period, respectively, the minimum, maximum, mean, standard deviations and number of iterations of the NPV and PBP are also indicated.

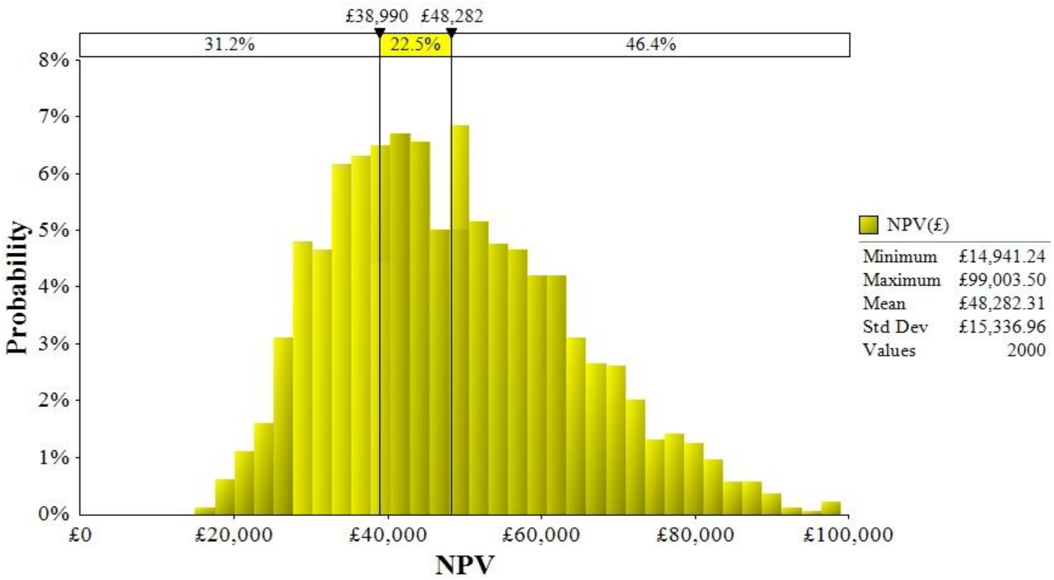


Fig. 15. Frequency prediction illustration of NPV

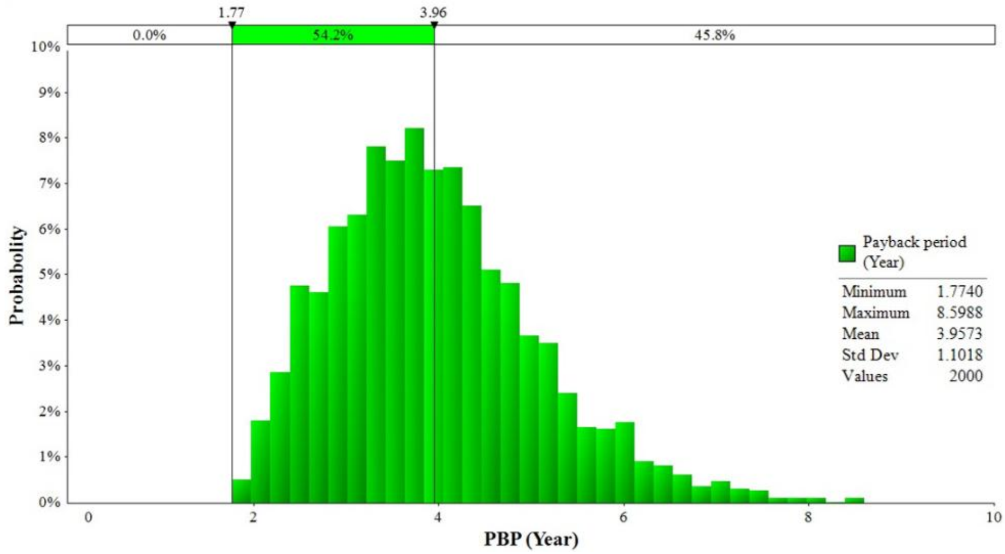


Fig. 16. Frequency prediction illustration of PBP

The vertical lines in Fig. 15 represent the NPV of present case (£38990) and average value (£48282). One row of percentages on the top of the diagram displays the probabilities relative to the NPV. Specifically, the top row depicts the probability regarding the LCC of the PV/T-HP system which is classified into three categories, it accounts for 31.2% when the NPV is less than the present case value; it makes up 22.5% when the NPV is located between the NPV of the present case value and average value; it accounts for a proportion of 46.4% when the NPV is greater than the average value. By contrast, the vertical lines in Fig. 16 denote the minimum (1.77 years) and average values (3.96 years) in the PBP. The top row of the graph, there is a probability of 45.8 % that the system PBP is more than 3.96 years, and 54.2 % of the payback time is between 1.77 and 3.96 years, while 0% of the payback period is less than 1.77 years.

The PV/T-HP system has the average NPV of £48282 after the 25-year running period, and there is nearly 22.5% possibility for this system to attain positive NPV (appreciated capital investment) between £38900 and £48282. By comparison, about 31.2% probability is lower than £38990 and 46.4% probability is higher than £48282. Based on the NPV decision-making regulation, the positive NPV illustrates that the capital investment on the presented system will be extremely cost-effective as the projected earning surpasses the expected expense. The average PBP is 3.97 years when the cash flow turns positive, as shown in Fig. 16. Similarly, there is 61.6% likelihood for the PV/T-HP system to attain a PBP less than 4.15 years, about 38.3% probability for the PBP is in the range of 4.15 to 8 years.

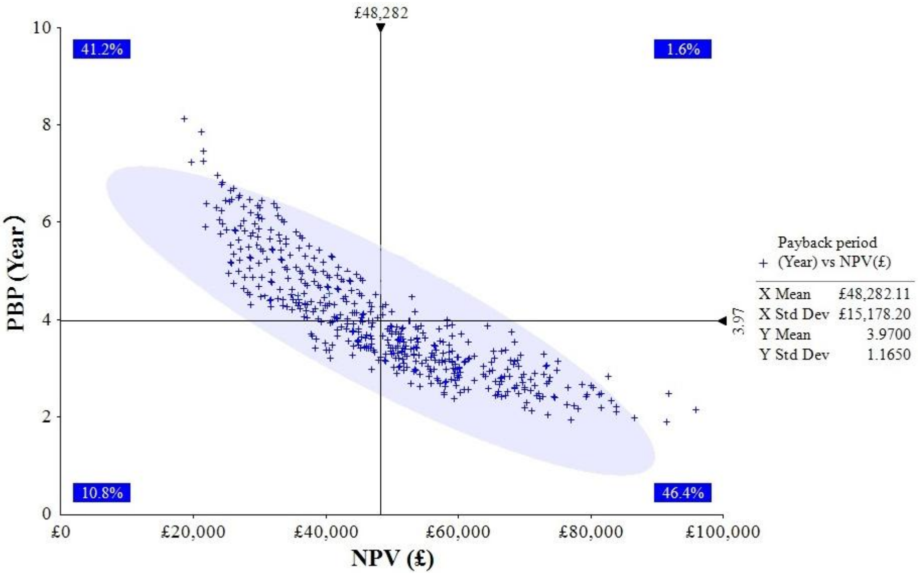


Fig. 17. NPV variation with PBP

The PBP has a probability of 46.40 % to be less than a mean value of 3.97 years as the NPV is superior to a mean value of £48282, as shown in Fig. 17. There is only 1.60 % probability that the PBP can be over 3.97 years when the NPV is above the mean value. This indicates that the long PBP is unfavourable to the NPV. If the NPV is less than £48282, there is likelihood of 41.20 % that the PBP is higher than the average value, while only an opportunity of 10.80 % is for the low PBP value. This demonstrates that the higher NPV can be obtained when the shorter PBP is achieved in the study. The Monte Carlo simulation is able to define the average annuity and the stochastic fluctuation risk more precise, and show the system's economic stability. The methodology is in accordance with the previous studies in terms of NPV and PBP [36, 37, 52, 53].

4.4.3 Comparison between FiT and SEG schemes

The Feed-In Tariff (FiT) scheme is a UK government programme designed to promote the uptake of renewable and low-carbon electricity production technologies. It was introduced on 1st April 2010 and closed for the new entry on 31st March 2019 [54]. Though the FiT has come to an end, the extra electricity produced by solar panels will inevitably goes back to the grid and as under current legislation it would be illegal not to be paid. Therefore, the UK government (Department for Business, Energy & Industrial Strategy) launched a new replacement scheme, named the Smart Export Guarantee (SEG), and ensures that eligible small-scale, clean electricity generators will, under law, receive payments from electricity suppliers such as SSE, EDF Energy, British Gas, npower, Octopus Energy and Scottish Power (those with more than 250,000 electricity customers) for each unit of electricity they export to the grid [55, 56]. The new scheme was set on 9th June 2019 and mainly comes into force on 1st October 2019, which commences on 1st January 2020 [57].

Under the SEG, customers are only paid for the metered electricity they export back to their electricity suppliers. There is no longer a “generation tariff”, so it is likely to take much longer before the capital investments are recovered by the SEG payments and energy savings [55, 56]. In comparison to the FiT scheme, the export price is not set by the UK government and there will be no long-term contracts. Based on this policy change, one of UK electricity suppliers like Octopus Energy has put forward two options with regard to the payments. One is a flat tariff called Fixed Outgoing Octopus that is a simple fixed payment for all surplus power exported to the grid at a fair market rate of 5.5p/kWh [58]. Another one is the flexible price called as Agile Outgoing Octopus that customers will get paid in the range from 4p/kWh to 9p/kWh at off peak time and from 10p/kWh to 15p/kWh at peak time [58]. This indicates that price changes at different time allow house owners generating renewable energy at home to taken into account the highly variable wholesale expense of energy throughout the day, and export at the most valuable times [58].

Based on new SEG policy, it can be observed from Fig. 18 that the annual electrical energy savings and income, under FiT, SEG with fixed export tariff and SEG with flexible export tariff schemes, can attain £2455, £616 and £1526, respectively. The FiT scheme could save approximately one time and twice as much costs in comparison to SEG with fixed export tariff and with flexible export tariff respectively. Similarly, the yearly energy savings and income under the FiT scheme is £10329 which is more than SEG with fixed export tariff of £8491 and SEG with flexible export tariff of £9400. Furthermore, the PBP under the FiT scheme is 4.15 years which is far less than SEG with fixed export tariff of 12.75 years and SEG with flexible export tariff of 9.33 years.

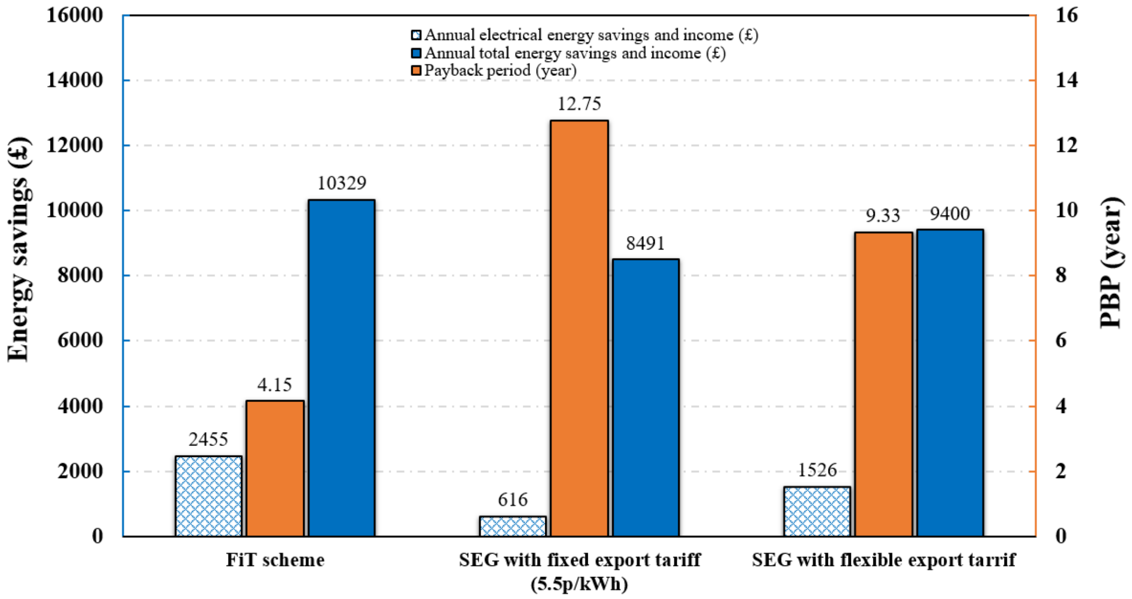


Fig. 18. Comparison of annual electrical energy savings and income, total energy savings and income and PBP between FiT and SEG schemes

The fact that there is no minimum to the export rate that energy companies must pay means that the government is envisaging a competitive market, but it will be difficult to make this happen artificially. That indicates that customers will likely experience very low export tariffs, much lower than with the FiT. That said, it is worth saying that this is a big step up from the previous government stance, no further subsidies of this nature would be thought until 2025. The SEG represents hope that the solar industry will not collapse entirely after the FiT has stopped taking new applications.

5. Conclusions

The energy performance and economic assessments of a hybrid PV/T-HP system are performed in this study. 18 CS6P-250P PV arrays with PHE are used in the PV/T module, and a 5.5 kW IVT Greenline heat pump is linked to the PHE to form the PV/T-HP system. The energy model of the PV/T-HP system is presented and used to evaluate its monthly electricity and heat generation, electricity consumption and COP via the EES software, the system economic model is set up through the Monte Carlo simulation which is solved using the @RISK software. A complete economic assessment is conducted considering the IC, ME, MP, SEC, EPT, ITS, PV/T-HP savings, NPV and cumulative savings, the sensitivity analyses of the NPV and PBP are also implemented. The key findings are concluded as follows:

- The PV/T-HP system could fulfil the building thermal and electrical demands from April to October and from May to August, respectively, and the extra electricity of 229.47 kWh is fed into the grid under the FiT scheme.
- The cumulative SEC savings (£12639) are in excess of the IC (£12015) at the end of the 4^{th} year, the cumulative PV/T-HP savings (£11758) exceed the remaining of principal balance (£9830) at the end of the 5^{th} year, and 4.15 years of the PBP is achieved.
- The PV/T-HP system with high NPV and short PBP has low initial investment.
- The Monte Carlo simulation is able to define the average annuity and the stochastic fluctuation risk more precise and thus enable a characterisation of the system's economic stability.
- The economic sensitive analyses reveal that the high discount rate reduces the system NPV whereas the high investment cost causes a long PBP to realize the positive NPV.
- Compared with the new SEG, the FiT is the most cost-effective scheme for renewable electricity generation and has the shortest PBP.

Appendix LCC of the PV/T-HP system for the domestic building in Nottingham throughout a 25-year operation period

Year	Energy generation (kWh/year)	SEC (£)	MP (£)	IP (£)	PP (£)	Principal balance (£)	Inverter replacement (£)	ME (£)	EPT (£)	ITS (£)	PV/T-HP savings (£)	Present worth of PV/T-HP savings (£)	Cum. PV/T-HP savings (£)	Cum. SEC savings (£)
0						10813.50					(1201.50)	(1201.50)	(1201.50)	
1	26338	2889.28	(927.91)	756.95	170.97	10642.53	–	(160)	(240.30)	699.01	2260.07	2078.23	1058.57	2889.28
2	26338	3062.64	(927.91)	744.98	182.93	10459.60	–	(167.20)	(249.91)	698.53	2416.15	2042.98	4315.95	5951.91
3	26338	3246.39	(927.91)	732.17	195.74	10263.86	–	(174.72)	(259.91)	697.97	2581.82	2007.42	6056.543	9198.31
4	26338	3441.18	(927.91)	718.47	209.44	10054.42	–	(182.59)	(270.30)	697.31	2757.69	1971.64	8814.23	12639.48
5	26338	3647.65	(927.91)	703.81	224.10	9830.32	–	(190.80)	(281.12)	696.54	2944.36	1935.73	11758.59	16287.13
6	26338	3866.51	(927.91)	688.12	239.79	9590.54	776.71	(199.39)	(292.36)	695.65	2365.79	1430.21	14124.38	20153.64
7	26338	4098.49	(927.91)	671.34	256.57	9333.96	–	(208.36)	(304.06)	694.64	3352.80	1863.82	17477.18	24252.14
8	26338	4344.41	(927.91)	653.38	274.53	9059.43	–	(217.74)	(316.22)	693.48	3576.02	1827.95	21053.2	28596.54
9	26338	4605.07	(927.91)	634.16	293.75	8765.68	–	(227.54)	(328.87)	692.16	3812.92	1792.23	24866.12	33201.61
10	26338	4881.38	(927.91)	613.59	314.31	8451.37	–	(237.78)	(342.02)	690.68	4064.35	1756.70	28930.46	38082.99
11	26338	5174.26	(927.91)	591.59	336.31	8115.05	900.42	(248.48)	(355.70)	689.02	3430.76	1363.54	32361.23	43257.25
12	26338	5484.71	(927.91)	568.05	359.86	7755.19	–	(259.66)	(369.93)	687.15	4614.37	1686.40	36975.60	48741.96
13	26338	5813.79	(927.91)	542.86	385.05	7370.15	–	(271.34)	(384.73)	685.07	4914.89	1651.71	41890.49	54555.76
14	26338	6162.62	(927.91)	515.91	411.99	6958.15	–	(283.55)	(400.12)	682.76	5233.81	1617.37	47124.30	60718.38
15	26338	6532.38	(927.91)	487.07	440.84	6517.31	–	(296.31)	(416.12)	680.19	5572.23	1583.39	52696.53	67250.76
16	26338	6924.32	(927.91)	456.21	471.69	6045.61	1043.84	(309.65)	(432.77)	677.35	4887.52	1277.09	57584.05	74175.09
17	26338	7339.78	(927.91)	423.19	504.72	5540.89	–	(323.58)	(450.08)	674.21	6312.43	1516.69	63896.47	81514.87
18	26338	7780.17	(927.91)	387.86	540.05	5000.85	–	(338.14)	(468.08)	670.75	6716.79	1484.00	70613.26	89295.04
19	26338	8246.98	(927.91)	350.06	577.85	4422.99	–	(353.36)	(486.80)	666.93	7145.84	1451.77	77759.10	97542.02
20	26338	8741.80	(927.91)	309.61	618.30	3804.69	–	(369.26)	(506.28)	662.73	7601.09	1420.01	85360.19	106283.80
21	26338	9266.31	(927.91)	266.33	661.58	3143.12	1210.09	(385.87)	(526.53)	658.13	6874.03	1180.86	92234.22	115550.10
22	26338	9822.29	(927.91)	220.01	707.89	2435.23	–	(403.24)	(547.59)	653.08	8596.63	1357.95	100830.80	125372.40
23	26338	10411.62	(927.91)	170.47	757.44	1677.78	–	(421.38)	(569.49)	647.55	9140.39	1327.67	109971.20	135784
24	26338	11036.32	(927.91)	117.44	810.47	867.32	–	(440.35)	(592.27)	641.49	9717.29	1297.91	119688.50	146820.40
25	26338	11698.50	(927.91)	60.71	867.19	0.12	–	(460.16)	(615.96)	634.89	10329.36	1268.65	130017.90	158518.90
Total												**38990.43**		

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Nomenclature

A	Area (m^2)
C_v	Clearance factor
D_H	Hydraulic dimeter (m)
d	Interest rate (%)
E	Expense (£)
f	Friction factor
Gr	Grashoff number
h	Heat transfer coefficient [W/(m·K)]
I	Incident solar radiation (W/m^2)
k	Discount rate (%)
L	PV panel length (m)
m	Mass flow rate (kg/s)
N	Number of time periods
Nu	Nusselt number
n	Polytropic compression coefficient
P	Pressure (k·Pa)
Q	Energy (kW)
T	Temperature (°C)

t	Time (s)
V	Wind speed (m/s)
V_c	Compressor swept volume (m^3)
W	Electricity consumption (kW)
x	Number of years before full recovery
Y	Number of mortgage payment years
y	Unrecovered cost at the start of the year (£)
Z	Principal payment (£)
z	Cash flow during the year (£)

Subscripts

absorber	Absorber
actual	Actual
air	Air
ave	Average
c	Glass cover
comp	Compressor
electricity	Electricity
fluid	Fluid
loss	Loss
pump	Circulation pump
r	Refrigerant
ref	PV module efficiency at reference temperature
s	Sky
thermal	Thermal
useful	Useful

Greek Letters

α Absorptivity

β Title-angle of PV panels

γ PV cell temperature coefficient (°C^{-1})

ω Compressor rotating speed (rev/s)

λ Thermal conductivity of air (W/m·K)

ρ Density (kg/m^3)

σ Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2 \cdot K^4$)

η Efficiency (%)

τ Transmittance

ε Emissivity

ξ Specific enthalpy (kJ/kg)

$\Delta\xi$ Specific enthalpy change (kJ/kg)

Abbreviations

AC Alternating current

COP Coefficient of performance

DC Direct current

EES Engineering equation solver

EP Emissive power

ET Export tariff

EVA Ethylene vinyl acetate

FIT Feed-in tariff

GHG Greenhouse gas

IC Initial cost

ITS Income tax savings

LCC	Life cycle cost
LCOE	Levelized cost of energy
LCOH	Levelized cost of heat
ME	Maintenance expense
MP	Mortgage payment
NPV	Net present value
PBP	Payback period
PC	Periodic cost
PHE	Polyethylene heat exchanger
PP	Principle payment
PV	Photovoltaic
PV-HP	Photovoltaic with heat pump
PV/T-HP	Photovoltaic/thermal assisted heat pump
RHI	Renewable heat incentive
SEC	System energy cost
SEG	Smart Export Guarantee
SHP	Solar thermal with heat pump

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***Declaration of Interest Statement**

Conflict of Interest and Authorship Conformation Form

Please check the following as appropriate:

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- The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript:

Author's name	Affiliation
Yuanlong Cui	University of Derby
Jie Zhu	University of Nottingham
Stamatis Zoras	University of Derby
Yaning Qiao	China University of Mining and Technology
Xin Zhang	Cranfield University